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Numerous research projects have examined the occurrences of air pollution in outdoor and workplace environments. A smaller, newer body of research has examined air pollution in nonworkplace, indoor environments. A new emphasis on measures to conserve energy in buildings, curbing heat loss through reduced indoor-outdoor air exchange, has encouraged interest in the relation between indoor and outdoor air quality, building energy conservation, and the potentials for adverse health effects from indoor air pollution in nonworkplace environments. A review of this body of research is the subject of this report. The preparation of this report required a comprehensive survey and assessment of the state-of-the-art of indoor air pollution research described in published literature and unpublished ongoing research.

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1976

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J.L.S.

Gaithersburg, Maryland
October 8, 1976

Section 1.0

INTRODUCTION

Much research has examined the occurrences of air pollution in outdoor and workplace environments. A smaller, newer body of research has examined air pollution in nonworkplace, indoor environments. A new emphasis on measures to conserve energy in buildings, curbing heat loss through reduced indoor-outdoor air exchange, has encouraged interest in the relation between indoor and outdoor air quality, building energy conservation, and the potentials for adverse health effects from indoor air pollution in nonworkplace environments. A review of this body of research is the subject of this report. The review was performed for the Environmental Monitoring and Support Laboratory of the U.S. Environmental Protection Agency, at Research Triangle Park, North Carolina, by GEOMET, Incorporated under Contract No. 68-02-2294, dated March 8, 1976.

1.1 SCOPE

The contract assignment which resulted in the preparation of the present report required a comprehensive survey and assessment of the state-of-the-art of indoor air pollution research described in published literature and unpublished ongoing research. GEOMET was requested to consider:

- Sources of air pollution in dwellings, schools, public buildings and vehicles
- Influences of outdoor air quality and meteorological conditions on indoor air quality

- Usage of products which serve as sources of indoor air pollutants
- Technology for monitoring indoor air pollution
- Mobility, dispersion characteristics, decay, and reactivity of indoor air pollutants
- Occupancy by humans of indoor air spaces
- Energy conservation measures presently being utilized in nonworkplace buildings
- Changes in indoor air quality as a function of energy conservation
- Health effects associated with characteristics of indoor air pollutants, including a rank ordering of air pollutants in terms of the hazard to human health resulting from their occurrence in nonworkplace indoor environments.

The basic survey and the preparation of its draft report were performed, as provided in the contract assignment, in the four-month period from March to July, 1976. Reviews of the draft by concerned EPA scientists and consultants were made between July and September, resulting in the completion of the report in October 1976.

This report is the culmination of the first phase of GEOMET's work under its EPA contract. A parallel continuing effort is the conduct of a program of field monitoring of indoor air pollution and energy use parameters in residences and schools which began at the end of June 1976 and is to be completed in the first half of 1977. The data from this program, with analyses and steps toward an improved indoor pollution model, will be available in a report to be issued in late 1977.

1.2 THE SURVEY PROCESS

The survey was performed through an examination of relevant published literature (reviewed journal articles, technical reports, and other publications) supplemented by personal communications with some researchers in the field. The literature examined was selected through the preliminary assembly and review of bibliographies of literature of likely relevance to indoor air pollution research. Research and documentation were considered relevant if they dealt with indoor air pollution in any of its aspects, with energy conservation measures which could affect indoor air quality, or with the health effects of pollutants in an indoor environment. Several approaches were taken to obtain bibliographies. These included:

1. Use of bibliographies previously prepared specifically for indoor air pollution research. Among these were *Indoor/Outdoor Air Pollution Relationships: Vol. II, An Annotated Bibliography*, EPA Publication No. AP-112b by J.J. Henderson, F.B. Benson and D.E. Caldwell, published in 1973; and a 190-entry bibliography of indoor air pollution research prepared by GEOMET from various sources in October 1975.
2. Discussion with EPA professional staff and with GEOMET consultants, for identification of relevant recent research papers.
3. Examination of recent volumes of *NTIS Air Pollution Abstracts* and *Environment Abstracts* and of such periodicals as *Journal of the Air Pollution Control Association*, *Environmental Science and Technology* and *Archives of Environmental Health*. References cited in relevant periodical articles were a further source of bibliographic information.
4. Visits to major libraries such as *National Library of Medicine*, the *EPA Library* at Waterside Mall, Washington, D.C., The *EPA Library* at West St. Clair, Cincinnati, the *DHEW Library* at the Parklawn Building, Rockville,

Maryland, the Library of Congress, the National Association of Home Builders Library, Washington, D.C., the libraries of the University of Cincinnati and Miami University (Oxford, Ohio) and others. Computerized bibliographic searches were made through the Smithsonian Science Information Exchange, through Medlars at the National Library of Medicine and through the National Agricultural Library at Beltsville, Maryland.

Where available, abstracts or summaries of articles identified in the bibliographic search were scanned. Articles which appeared to be relevant on the basis of abstract, summary, or title (if only the latter were available) were obtained and examined. If relevance was confirmed the document was listed for inclusion in the Bibliography (Appendix B) of the present report. In general, documents listed in Appendix B have been examined by authors of this report. This is not always the case. Some documents not examined are listed only because their relevancy was cited by researchers whose studies are referred to in this present report.

1.3 THE SURVEY TEAM

This report has been prepared by a multidisciplinary project team directed by GEOMET, Incorporated. GEOMET provided overall management for the literature review and report production, and members of the GEOMET staff undertook the health effects, air quality analysis, and modeling aspects of the study. GEOMET was supported by the efforts of two subcontractors: Hittman Associates, Inc., for energy conservation and PEDCo Environmental Specialists, Inc. for air pollution monitoring technology. GEOMET consultants from several universities, in the fields of epidemiology, monitoring, and modeling of indoor air pollution, have provided advice to the project.

Section 2.0

AN OVERVIEW OF INDOOR AIR POLLUTION RESEARCH

Air pollution and its effects on human health have been studied in outdoor, industrial and indoor environments. This report is concerned with indoor air pollution research, and particularly with residential and other nonworkplace indoor environments.

2.1 ELEMENTS OF INDOOR AIR POLLUTION RESEARCH

Indoor air pollution research is potentially a large field. It is defined, for the purposes of this report, to include the following areas of study:

- Sources of indoor air pollution
- Distribution and behavior of indoor air pollution
- Monitoring (measurement) technology for indoor air pollution
- Building occupancy and human exposure to air pollution
- Energy conservation measures in buildings which may affect indoor air quality
- Health effects of indoor air pollution
- Modeling (estimation and prediction) of indoor air pollution behavior.

Published literature and other available information in these fields are described in this report. Emphasis has been placed upon research in the nonworkplace, indoor environment, but the study cannot easily be so constrained.

Much relevant research has been performed in environments which do not meet the basic criterion of being "nonworkplace." University and private laboratory buildings have been sites of important research in emissions of indoor-generated pollutants and of research into indoor-outdoor air pollution concentration ratios. Hospital environments have been monitored for allergen and other biological aerosol concentrations. Work performed in such areas has been referred to in this report when its results appear to be also applicable to nonworkplace environments.

In the field of health effects of indoor air pollution it is especially necessary to examine studies which are not limited to residential and other nonworkplace environments. With the exception of the consideration of clinical effects of carbon monoxide exposure there have been few clinical or epidemiological studies of the impact of indoor air pollution upon human health in which any effort was made to identify the human exposure indoors, within residences, public buildings, schools or vehicles, as being a separate category of air pollution exposure. More typically, health effects studies have correlated health status changes with ambient (i.e., outdoor) air pollution levels, or with specific and (from the point of view of the nonworkplace environment) unusual exposures of individuals to air pollution in industrial workplaces. The effort made in the present report, to appraise the status of research in and knowledge about indoor air pollution health effects, therefore draws upon the broad base of research performed in industrial environments and in the general field of ambient air pollution epidemiology as well as upon research in nonworkplace indoor environments.

In the discussions which follow immediately, Sections 2.3 through 2.9, the state of research in the seven areas of interest is summarized briefly. No literature citations appear here, but the text is based in each case upon a more detailed exposition given later in Sections 3 through 9, where specific literature citations will be found for all statements and conclusions drawn from the work of researchers in the indoor air pollution field.

2.2 THE NEED FOR INDOOR AIR POLLUTION RESEARCH

Why make a special study of indoor air pollution? Are its characteristics and consequences sufficiently different from air pollution in the already active fields of ambient and occupational air pollution research to justify the definition of a new field of study? The answer appears to be yes.

The major thrust of air pollution research, and of air pollution control and regulation, has historically been toward protecting human health and welfare from air pollution damage in outdoor and occupational situations. These two contexts each have characteristic and quite different air pollutant species, concentrations and human exposures. There is a reasonable presumption, borne out by the research reviewed in this report, that the indoor nonworkplace environment represents a third major context - one in which the pollutant species present, their concentrations, and the nature of human exposure are significantly different from the situations which prevail outdoors and in workplaces. Further, the nonworkplace, indoor environment is one in which many people - particularly homemakers, children and the elderly - spend the major part of the time. The air pollutants to which they are exposed are not necessarily those of ambient air. As the details of this report will show, pollutants occurring within buildings may reach levels at which exposures of significant importance to health occur. The character, intensity and duration of these indoor air pollution exposures are unlike those occurring in the better studied ambient and occupational contexts, sufficiently so to require new research into their origin, behavior and consequences.

The differences between indoor and outdoor pollution exposures, and the potential consequences of indoor pollution exposures, may in the future justify the setting of national standards directed toward the control of nonworkplace indoor air pollution levels in the protection of human health and welfare. There are as yet no such standards. Research into the occurrence and consequences of indoor air pollution is an essential prerequisite for defining the hazard and designing means for its control.

There is enough evidence now to make it clear that a potential indoor air pollution health problem exists. More research is needed to determine its extent and amenability to management. The status of current research is described in some detail in the main text of this report, Sections 3 through 9. An overview of this research appears below.

2.3 SOURCES OF INDOOR AIR POLLUTION

There are two major source categories of indoor air pollution: (1) infiltration from outdoor ambient air and (2) generation of pollutants in the indoor environment.

Pollutants entering buildings from outdoor ambient air include sulfur dioxide, nitrogen oxides, carbon monoxide, hydrocarbons, oxidants, and suspended particulates (i.e., the so-called "criteria" pollutants for which National Ambient Air Quality Standards exist). Other pollutants of outdoor origin for which researchers have considered indoor/outdoor concentrations have included the respirable fraction of particulates, trace metals, biological aerosols, carbon dioxide, carbon disulfide, hydrogen sulfide and peroxyacetyl nitrate (PAN). For almost all outdoor-generated pollutants, researchers have found that concentrations indoors are lower than outdoors (unless there is a separate source for generation of the pollutant within the building). Indoor-outdoor ratios are high, approaching and sometimes exceeding unity, for carbon monoxide (an unreactive gas). Sulfur dioxide and ozone react chemically with substances in the indoor environment and hence show typically lower indoor-outdoor pollutant concentration ratios (varying from 0.20 to 1.0 for sulfur dioxide, 0.65 to 1.0 for ozone). Suspended particulates show concentration reductions below outdoor levels, although indoor sources of particulates and lack of particulate size distribution studies make the significance of indoor-outdoor ratios for particulates unclear. There is little information on indoor-outdoor ratios for nitrogen oxides and hydrocarbons; the few studies noted suggest that indoor-outdoor concentration ratios are high.

Actual measurements of the effective source strengths (i.e., of the sum of planned and unplanned infiltration into the building) have not often been made for outdoor-generated pollutants. Ozone infiltration rates have been calculated with the aid of tracer studies and a theoretical model, but the more typical research procedure has been to simply measure pollutant concentrations (parts per million by volume, or weight of pollutant per unit volume) inside the building and outside it. The resulting indoor-outdoor concentration ratio, generally reported in the literature, is related to the rate at which the pollutant enters the building but it cannot be used alone to calculate source strengths. The indoor-outdoor concentration is dependent not only upon the entry rate of the pollutant but also upon the relative locations of indoor and outdoor sampling points upon the internal ventilation system of the building, the time periods involved in monitoring, and upon the reactivity of the pollutant with substances within the building. With the exception of some measurements for ozone, there are no indications in the literature of the quantities and rates in which outdoor-generated pollutants enter buildings.

Indoor-generated pollutants include carbon monoxide; carbon dioxide, nitrogen oxides and sulfur dioxide from indoor combustion; particulate matter and chemical vapors from household cleaning; halogenated hydrocarbons from solvents; mercury from paints; propellants and active ingredients of aerosol spray products; carbon monoxide, particulates, nicotine and other chemicals from smoking; aldehydes from cooking and many others. There has been considerable research into combustion product pollutants in the indoor environment, including measurements and calculations of source strengths. Estimates of pollutant emissions have been made for aerosol spray product propellants, and to some extent for the airborne pollutant products of smoking. Emission rates for the active ingredients of aerosol spray products have been difficult to estimate in the absence of sophisticated monitoring and laboratory technology - because the exact nature and proportions of such ingredients are proprietary information not usually disclosed by manufacturers. Source strengths have typically not been reported in the literature for the "fugitive" type of indoor pollutant emissions, such as those arising from diffuse sources in cleaning, food preparation, pesticide application, painting and hobby activities.

2.4 DISTRIBUTION AND BEHAVIOR OF INDOOR AIR POLLUTION

The concentration, residence times and decay rates of the standard major ambient air pollutants, SO_2, NO, NO_2, CO, O_3 and suspended particulates (also called the National Ambient Air Quality Standard criteria pollutants) have been extensively studied in indoor environments. Much of this research has been concerned with indoor-outdoor concentration ratios, evidence of a tacit assumption by many researchers that outdoor sources of air pollution are the important ones for indoor air pollution.

Building ventilation and indoor climatology have a major influence on the transport, diffusion and removal of indoor pollutants. These influences have been studied for the standard pollutants in the indoor-outdoor context. Data collected in these studies typically provide gross or partial measures of pollutant behavior, without the fine structure needed to permit the making of conclusions about dimensional pollutant gradients and behavior within a building. The building (indoor space) is generally treated as a plenum (or whole) interacting with the outdoor space. Differing air pollution characteristics in different parts of a building - necessary to determine human pollutant exposure and dosage - have not often been considered in research performed in the past. Research data on the indoor decay of introduced ambient reactive pollutants show definite relationships between pollutant decay and indoor climatology. There appears to have been no important research dealing with indoor chemical formation of secondary pollutants, e.g., sulfates and nitrates. In general, the area of chemical transformation and fate of indoor pollutants has not been addressed in depth.

Data on indoor emissions (source strengths) of the standard pollutants are uncommon in the literature, except for measurements on the production of carbon monoxide and nitrogen oxide in gas stoves. This scarcity is probably a function of the considerable technological difficulty in making emission measurements of the uncontrolled generation of air pollutants when these appear indoors from stoves, leaky furnaces, smoking and other diffused sources. Measurements of quantities of propellants in aerosol sprays, and of some combustion products of tobacco smoking, have been made; these are essentially calculations of source strength from known ingredients rather than actual measurements. Aerosol and smoking pollutant source strengths have been correlated with pollutant concentration measurements to produce information about decay rates; but such source strength-indoor concentration comparisons are rare in the literature of research into indoor-generated pollutants. The data tend to be partial, providing pollutant concentrations but not pollutant behavior histories.

2.5 MONITORING TECHNOLOGY FOR THE MEASUREMENT OF INDOOR AIR POLLUTION

Indoor air quality monitoring technology relies heavily upon the technique and instrumentation earlier developed for ambient air monitoring and for industrial hygiene monitoring. Adaptations in technology must be made for the special circumstances of the indoor environment.

In outdoor (ambient) air pollution monitoring the instruments used for making measurements do not significantly alter the environment in which they operate. They are infinitesimally small in physical size and in air intake requirements compared to their environment. This is not the case for indoor air monitoring. A high volume air pump of the type conventionally used to monitor ambient particulate through trapping particles on a filter for weighing could sensibly alter the concentration of particulates in the air inside a house because its flow rate is high enough to exchange all the air in a large room in an hour. Further, the size and noise of its operation would impede normal use of any indoor space in which it is placed. Instruments for indoor use must be physically smaller than outdoor instruments. The analyzers, filters and pumps may need to be located remotely from the sampling points. Flow rates of intake air must be small and this often requires higher threshold detection levels and instrument sensitivities than are customary in ambient air monitoring.

The range of pollutants to be monitored is wide; wider than the usual outdoor ambient concern which is largely limited to the National Ambient Air Quality Standards criteria pollutants, their transformation products and trace metals. Many of the pollutants of concern in indoor residential spaces have been routinely monitored in the past only under laboratory conditions or in industrial situations where the pollutant concentrations are high.

Many indoor-generated pollutants are emitted in a "fugitive" manner, i.e., they enter the atmosphere through uncontrolled emanation from surfaces, leaks from faulty combustion systems, or from other sources ill-defined in place and form. It is difficult to measure source strengths for such pollutants; conventional emissions monitoring techniques are not applicable. Innovative measurement techniques, involving combinations of pollutant concentration monitoring, controlled tracer gas measurements and simulation modeling may be required.

One approach to the problem of avoidance of altering the indoor environment through monitoring has been to place the analyzers, filters and pumps in a mobile monitoring van located outside the building in which pollutant behavior is to be measured. The sampling inlets, located in the building, are connected to the analyzers by long, small-diameter, flexible tubing passing through closed windows or other openings in the building's outside wall. Special problems of air flow and possible pollutant loss in the tubing are involved; but these are solvable.

The instruments used in indoor air monitoring operate upon physical and chemical principles already demonstrated, for the most part, in ambient and industrial air pollution monitoring. The differences are in the details required for the special indoor conditions suggested above, not in principles.

2.6 HUMAN OCCUPANCY PATTERNS IN INDOOR SPACES

Levels of indoor air pollution are in part a function of the activities of occupants of indoor spaces. People affect the indoor-outdoor pollutant concentration relationships by opening and closing doors and windows and by controlling operations of heating, ventilating and air conditioning systems. People also create indoor air pollution inside buildings through such actions as sweeping, using aerosol sprays, cooking, smoking and breathing.

The hazard of air pollution to human health is a function of pollutant toxicities and human dosages. Dosages are functions of exposures, which in turn are functions of the strengths, durations and locations of pollutant concentrations and of the locations and types of activity of people who occupy the spaces contaminated by air pollution. For these reasons studies of human movement and activity in buildings are needed to (1) provide additional information about indoor pollutant generation and distribution and (2) make it possible to estimate human exposure to indoor air pollution; but few studies directed towards those objectives have been undertaken.

Occupancy profiles have been developed by investigators, displaying the levels of occupancy in buildings as a function of time. These are typically gross patterns, showing occupancy of an entire building averaged over periods of an hour or more. They are of more value to the design of heating, ventilation and air conditioning systems than they are for indoor air pollution generation and exposure studies. A finer detail of the time and place of indoor human movement is required than appears to be now available in the scientific literature.

Activity patterns add some of the desired detail, by classifying human activities into various categories which can be at least indirectly related to pollutant-creating or pollutant exposure situations. But studies of activity, as performed in the past, do not yet adequately relate activity events inside buildings to the times and places at which pollutant concentrations may be measured or predicted.

2.7 ENERGY CONSERVATION MEASURES AND THEIR RELATION TO INDOOR AIR QUALITY

Energy is supplied to buildings to maintain indoor conditions of temperature, humidity and air flow which meet human requirements for health and comfort. These conditions are maintained by the static considerations of building design (orientation, layout, volume, shape, materials, planned openings - windows and doors - and unplanned openings - cracks - in the exterior wall) and the dynamic operation of the building heating, ventilation and air conditioning (HVAC) system including mechanical equipment and window opening and closing. Energy is required to operate the HVAC system. The HVAC system moves energy in the building, as heated or cooled air, and transfers energy from the building to the outdoors by venting air. Energy also enters the building from the outdoors whenever exterior temperatures are higher than interior if building design and operation does not prevent the heat transfer.

Energy can be conserved in buildings by minimizing heat flow from the building to the outside. This can be done by methods which affect building air change rates, reducing the flow of air between indoors and outdoors, and by methods which do not directly affect air change rates.

Among the possible structural modifications which save energy by reducing air change rates are installation of storm doors and windows to reduce infiltration (air leakage), caulking and weatherstripping, painting, use of smaller windows, improved orientation of the building with respect to wind and sun exposure, elimination of fireplaces, use of recirculating kitchen hoods, vestibule doors, door closers, and windbreak landscaping.

Structural building modifications which save energy but do not directly affect air change rates include: insulation of walls, roofs and floors, double-glazing of windows, improved thermal capacities of building materials, shading for windows, fluorescent lighting instead of incandescent, elimination of gas-burning pilot lights, reduction of the ratio of building envelope to floor area, ventilation of attic spaces, using appropriate external building colors, and lower ceiling heights.

Modifications to the HVAC system and its operation which save energy by reducing the indoor-outdoor air change rates include installation of flue dampers, use of outdoor air for combustion, installation of an economizer air conditioning cycle, internal pressurization, filtration and re-use of ventilation air, reduction in percentage of outdoor air intake, reduction in ventilation rate, and improved ventilation control.

Modifications of the HVAC system to save energy which do not affect air change rates include: recovery of flue gas heat through heat exchange devices, zone control of the HVAC system inside the building, separate make-up air for high exhaust rate areas, humidity control, proper sizing of equipment, improved furnace design, nighttime temperature setback, and regular maintenance.

Human life-style habits also impact on energy use and loss in buildings. Energy savings can be achieved by keeping windows closed, minimizing use of exhaust vents, minimizing exit and entry to buildings - all these reduce air change rates. Life-style habits which save energy without directly affecting air change rates include use of lower thermostat settings in winter and higher settings in summer, reduced use of large appliances and lower lighting levels.

All the energy conservation actions which reduce indoor-outdoor air change rates also impact directly on indoor air pollution levels, essentially by tending to reduce the indoor levels of outdoor-generated pollutants, while increasing residence times of indoor-generated pollutants. The operation of the HVAC system, if it is equipped with filters, precipitators or washers, may remove some portion of the particulate matter in the air and some portion of the reactive pollutant indoor air concentrations of species such as SO_2 and oxidants. A reduction in air change rates may reduce this removal rate, resulting in somewhat higher levels of pollutants than might otherwise be expected; this effect is small and may be masked by the reduction of infiltration of outdoor pollutants. Changes in building temperature and humidity impact upon decay rates of reactive pollutants; typically decay rates increase with rising temperature and humidity, meaning that the pollutant concentrations reduce more rapidly. This may or may not be desirable from the health point of view, since the pollutant transformation products in conditions of heightened temperature and humidity may adversely impact on health.

There have not been quantitative studies linking measured parameters of energy conservation, and of HVAC operation for energy conservation, with changes in indoor air pollution levels. Such studies are a desirable objective for future research.

2.8 HEALTH EFFECTS OF INDOOR AIR POLLUTION

Many people spend a major part of their lives in nonworkplace indoor air environments, exposed to air pollution which differs significantly, in type and level, from the better-studied ambient and occupational air environments. What are the health hazards of these exposures?

The question has been little studied in the specific context of the nonworkplace indoor environment. Population studies correlating general ambient air pollution levels and health status are reported in the literature for the more common, widespread ambient pollutants; a number of these studies have considered synergistic effects of pollutant combinations. Such studies in years prior to 1971 were the basis for the establishment of National Ambient Air Quality Standards for the six "criteria" pollutants - sulfur dioxide, carbon monoxide, nitrogen oxides, photochemical oxidants, total nonmethane hydrocarbons and total suspended particulates - to protect public health and welfare. Many other studies of health effects of specific pollutants have been made in the context of occupational exposures, often dealing with pollutant concentrations higher than would usually occur in other environments. The scientific literature relevant to indoor air pollution is largely to be found in these related fields of ambient and occupational air pollution health effects.

The review upon which this report is based has examined the literature for the purposes of (1) identifying the health effects of those pollutants most likely to occur in nonworkplace indoor environments, (2) considering the interactive effects of pollutants, (3) considering the susceptibility of population subgroups to indoor air pollution hazards, and (4) attempting to develop a rationale for appraising the relative health hazard of various indoor pollutants.

Indoor, outdoor and occupational air pollution health effects cannot readily be separated. The effort here is not to consider the health effects of indoor air pollution in isolation, an impossible task, but to examine the existence and role of indoor air pollution as a significant factor in the overall problem of air pollution impact upon human health.

From the literature of general and occupational air pollution health effects studies, there is adequate evidence to substantiate the health hazards, indoors and outdoors, of the so-called "criteria" air pollutants. The level of knowledge about the health effects of these major air pollutants is uneven. The synergistic effects of SO_2 and particulates and of SO_2 and sulfates in producing both acute and long-term respiratory system problems are well documented, but the adverse impacts of SO_2 alone at common ambient levels are less well understood. Sulfur dioxide exposure is probably typically lower indoors than outdoors. The dose-effect relationship of carbon monoxide is well-established and a substantial amount of research into its cardiovascular impact continues. The subject is an important one because carbon monoxide may occur at high indoor levels from several sources, including gas stoves and smoking. Carbon dioxide, a noncriteria pollutant but one which may occur in high levels indoors, can produce adverse health effects through oxygen deprivation, but the evidence suggests that pollutant levels high enough to cause this will be rare in nonworkplace indoor environments. Nitrogen dioxide has been less studied than sulfur dioxide and carbon monoxide; its correlation with acute respiratory disease has been demonstrated and studies of this aspect continue. Nitrogen dioxide has also been implicated in long-term respiratory problems and with increased mortality from cardiovascular disease and cancer, although the evidence is less clear than for acute respiratory disease. Like carbon monoxide, nitrogen oxides are a potentially common indoor pollutant associated with gas stoves. Photochemical oxidants have well-documented, short-term irritative effects but long-term effects are not well understood; however, they may not be a significant indoor problem because of the rapid decay of reactive oxidants in indoor environments.

Total suspended particulates, a "criteria" pollutant, are implicated as a group in short-term pulmonary health effects, particularly in the severity of asthma attacks. Among particulate components, lead, aluminum and asbestos have been reported in indoor air at concentrations which could result in increased blood levels (for lead), pulmonary effects (for aluminum), and mesothelioma (for asbestos). Cadmium and nicotine are among other particulate products of tobacco smoke which have a potential for health damage as components of the indoor air environment.

The hydrocarbons are a diverse group including many pesticides, propellants and solvents which may be present in indoor environments in high short-term concentrations or in continuous lower-level concentrations quite unlike typical ambient or occupational levels. Chemically, many of these are halogenated hydrocarbons which have been implicated in liver and respiratory system pathology, are neurotoxic, and have caused cancer in animals. The vapors from one common solvent, methylene chloride, metabolize to carbon monoxide in the human body resulting in elevated carboxyhemoglobin levels. Pesticides may also contain organophosphates which impact acutely upon the nervous system.

Smoking represents a special indoor air pollution health hazard through its production of indoor air concentrations of carbon monoxide, trace metals, nicotine and many other toxic, organic chemicals. The health effects of tobacco smoke have been widely studied, although more in the context of the active smoker than of the nonsmoking individual exposed to smoke-contaminated air. Documentation of the health hazard of this aspect of smoking is sparse.

The synergistic action of particulates and SO_2 correlating with an increase in adverse health effects, seems to be well established. Some evidence is available implying a similar action among particulates, NO_2 and oxidants. There is less evidence for other synergistic effects, although studies available suggest an additive effect on lung cancer of exposures to POM (polycyclic organic matter) from smoking, occupational pollutants, and ambient pollutants.

Several studies have investigated the contributions (individually and in combination with various pollutants) of temperature and humidity. The CHESS studies imply that the ambient pollutants contribute more to aggravation of respiratory disease at higher temperatures. PAN (peroxyacetyl nitrate) appears to be more potent at higher temperatures. Another study concluded that increasing the relative humidity of occupied spaces reduced the relative incidence of respiratory conditions in school children.

Available information indicates that young children, the elderly, and those with chronic respiratory problems are in general more sensitive to irritant gases and particulates. Some asthmatics are particularly sensitive to irritant gases and particulates. Anemics are theoretically more susceptible to CO and NO_2, and persons with low cardiac reserve or high COHb levels could also be jeopardized by ambient CO levels. Although the factors in lead intake and balance are not well established, children or workers who may already have a high lead blood level could possibly achieve clinically important burdens from respiration of ambient lead concentrations.

Research priorities in indoor air pollution ought to bear a relation to the health hazards of the various pollutants. A ranking of pollutants in terms of the hazards they present in the indoor environment is conceptually possible, but its practicable realization is extremely difficult.

The health hazard from an indoor air pollutant is a function of the following elements:

1. The levels at which it occurs indoors
2. The frequency with which it occurs indoors
3. The extent to which individuals are exposed to the pollutant
4. The exposure-response health effect of the pollutant
5. A judgement of the relative disbenefits to society of the various possible health effects.

These elements are potentially quantifiable to society as a whole, and from them a ranked order of the hazards of each indoor air pollutant could be developed. Reliable data for Items 1 through 4 are difficult to obtain, increasingly so as one goes down the list. Quantification of Item 5 must be judgemental, probably arbitrary, and certainly controversial. The subject is addressed, but not resolved, in Section 8.0 of this report.

Considering the concept of such a ranking, but without hard numbers to support the conclusion, it may be suggested that the following rough combined priorities, of health hazard and need for further research into specific indoor air pollutant research, exist on the basis of present knowledge of:

1. Carbon monoxide, nitrogen oxides and sulfur oxides
2. Tobacco smoke and its products
3. Chlorinated hydrocarbons and organophosphates in pesticides
4. Fluorocarbons in propellants
5. Lead, cadmium, arsenic and aluminum

These air pollutants are listed in this order on the basis of their ubiquity in nonworkplace indoor air environments, the extent to which substantial health hazards have already been identified, and the extent to which the existence of the hazard and current lack of data suggests that further research is needed.

2.9 MODELING OF INDOOR AIR POLLUTION

Important objectives in studying indoor air pollution are to obtain a better understanding of the potential health hazard and to obtain information upon which methods for controlling indoor air pollution, thus mitigating the health hazards, can be based. The achievement of these objectives, even a partial achievement, requires the development of models which can describe the interactions of indoor air pollution, with the indoor environment and with people in that environment.

Useful models have two common attributes: they simplify complex situations and they have a predictive capability. A model provides numerical relations between inputs (e.g., air pollution levels, human occupancy habits, and structural characteristics of buildings) and outputs (e.g., air pollution exposures, health effects). No model is a perfect representation of reality. Workable models of complex processes are highly imperfect representations; their relative simplicity requires that this be so. But they are considerably better for predicting outputs than the alternative of guessing.

A complete mathematical model of the indoor air pollution problem would enable a researcher, given appropriate input information about air pollution sources and other factors, to calculate health hazards in any indoor environment. Some of the input data for that model would be extremely difficult to obtain. With the present inadequate state of knowledge of factors affecting indoor air pollution and human health, the model's results would be of doubtful validity. The complexity of the model, even with much necessary simplification, would probably make it costly to operate. But despite these problems researchers have considered it desirable to move toward developing such models. Models are one of the keys to understanding and correcting the problems of indoor air pollution.

A model with an output which quantifies the health hazard (or health effect) of one or more air pollutants in an indoor, nonworkplace environment should have the following classes of inputs:

- Ambient outdoor air pollution
- Climatology and meteorology
- Building design and siting elements
- Heating, ventilation and air conditioning characteristics of the building
- Indoor air pollutant sources
- Indoor/outdoor energy flow
- Building occupancy characteristics, including personal habits of the occupants
- Mobility patterns of the occupants within the building over time
- Personal health status characteristics of the occupants
- Toxicity of the pollutants, in terms of dose-response
- Exposure and dosages of air pollutants experienced by the occupants when away from the building.

No such general model exists, although several efforts to design indoor pollution exposure models, having much of this input, are now in the planning stages. A large model of this kind could be created through the joining together of less ambitious models which seek to describe and quantify only a subset of the major elements.

The present report reviews the literature of analytical modeling studies of indoor air pollution relationships. Specifically examined is the state-of-the-art of definition of the following model parameters: pollutant source strengths, decay rates, indoor environmental parameters, structure identification parameters, and the impact of human activity. Energy load and consumption models are reviewed briefly; these relate building energy requirements to structural and HVAC considerations and have no direct output which can be used to quantify indoor air pollution concentrations. Three existing models which simulate building infiltration and air movement within a building are described. Finally, five existing indoor/outdoor ventilation models with indoor air pollution calculation capabilities are reviewed. These models are considered in the order of their increasing sophistication and capability. These models have many common features and represent a consistent line of research development. But at their best they are highly constrained procedures for calculating gross indoor air pollution concentrations in an idealized building. Much more work is necessary to develop models which can reliably predict pollutant concentrations in the complex environments of ordinary residences, schools and public meeting places. No models now exist which can predict air pollutant dosages and health hazards in such an environment.

2.10 AREAS OF FURTHER RESEARCH INTEREST

The efforts to develop air pollutant hazard ranking models and less ambitiously to develop indoor pollution concentration and exposure models, are essentially efforts to characterize the indoor air pollution problem as an integrated whole. The act of attempting to develop such models has the highly valuable effect of demonstrating where important knowledge gaps are. For an understanding and resolution of indoor air pollution problems the information input for these models is needed, even if the models themselves are never developed in the forms conceived here.

On that basis priority areas for future research may include:

- Further studies of the indoor source strengths, concentrations, behavior and frequency of occurrence of SO_2, CO, CO_2, NO_x, sulfates, nitrates, halocarbons, organophosphates and trace metals in a wide variety of indoor environments
- Occupancy and mobility studies of the ways in which people use indoor environments, including studies oriented toward susceptible population subgroups
- Studies of the epidemiology of air pollution which consider the totality of ambient, occupational and indoor pollutant exposure
- Air exchange patterns of buildings as functions of structural and operational characteristics.

In the broad field of health effects of indoor air pollution it is appropriate to consider a range of questions relating to the absorption and clearance of pollutants in man and their health effects:

Absorption and Clearance in Man

- What is the Nature of Exposure? Since the absorbed dose, and thus the biologic effect, will vary with the exposure, it is necessary to characterize the exposure as infrequent, intermittent, and persistent. Since the exposure of different household members (i.e., to the byproducts of gas used in cooking) is varied, a method of assessing this characteristic must be considered.

- What are the Pathways of Absorption? Multiple sources of entry (skin, respiratory tract, eyes) may be pertinent and from other media (food and water) than air.

- What Early "Mechanical" Clearance Mechanisms Exist for the Agent? Is the agent cleared by ciliary action? Trapped in the mucus of the upper respiratory tract? Swallowed and excreted in feces?

- How and to What Degree (Following Mechanical Clearance) is the Agent Absorbed? While much valuable data has been collected which directly relates the degree of exposure to physiologic and pathologic effects, there is increasing recognition that a better understanding of the absorbed dose and its subsequent fate in the human is of great importance.

- Following Absorption, What Clearance Mechanisms Exist? The original agent may be converted to a more toxic product or carcinogen within the body. In the clearance and metabolism process, a number of different tissues may be exposed and each may differ in sensitivity to the chemical. Interpretation of dose-response must consider each type of tissue affected. This is particularly important in evaluating low-dose, chronic exposure and its consequences. In addition to carcinogenesis and mutagenesis, other questions, such as whether autoimmune disease results from continuous exposure to concentrations which produce no observable acute effects, must be considered.

- Following Clearance, is there Significant Deposition of the Agent in Human Tissue? Where? What is the Expected Dose-Body Burden? The agent's deposition in tissue is clearly of great significance. For example, asbestos fibers of appropriate size which lodge in the lung, cause clear-cut pulmonary disease. The site of the carcinogenic process is determined by:

  - The physical and chemical properties of the agent
  - The type of contact with the host

- The mode of clearance
- The fixation in particular organs - in general the the carcinoma arises at those sites where the carcinogen has the most prolonged and intense contact with the tissues.

The investigator must also consider other factors such as: Will the current exposure add to the existing body burden of the agent and other substances which may be byproducts of the clearance process? Does the agent inhibit the clearance mechanism of a second pollutant and thus increase the latter's body burden?

Human Health Effects

- What is the Direct (Immediate) Physiologic Response of Tissues Exposed to the Agent in Varying Dosages? Lachrymation, respiratory irritation?
- What Effects Occur Due to the Clearance Mechanism? Are clearance byproducts carcinogenic, or do they cause other types of adverse physiologic or pathologic response?
- What Effects are Related to the Deposition of the Agent in the Tissues? At What Body Burden?
- What Synergistic or Additive Effects are Known to Occur Between the Agent and Other Exogenous Agents in the Human? The synergistic action of particulates and SO_2 seems to be well established. Some evidence implies a similar synergism between particulates, NO_2 and oxidants.
- Is there Specific Group Susceptibility to the Agent?

These examples of areas for future research directions are drawn from the appraisals made as the literature of indoor air pollution was reviewed for this report. Other specific suggestions appear in the detailed text which follows.

Section 3.0

SOURCES OF INDOOR AIR POLLUTANTS

Air pollution in the indoor environment (e.g., in dwellings, schools, public buildings and vehicles) originates from two categories of sources; (1) air pollution in outdoor ambient air which enters the indoor environment through ventilation and infiltration, and (2) air pollution which is generated indoors. As research subsequently cited in this report will show, some indoor air pollutants originate in significant quantities in both categories, carbon monoxide for example; some appear in the indoor environment in significant measure only from outdoor sources, PAN (peroxyacetyl nitrate) is an example; while others arise primarily from indoor generation, as in the case of the fluorocarbons used as propellants in aerosol spray products. Discussions of the sources of these and other pollutants, with appropriate literature references, are presented in the following pages. The review of research literature is presented in two categories, pollutants of outdoor origin and pollutants of indoor origin.

3.1 OUTDOOR AMBIENT AIR AS A SOURCE OF INDOOR AIR POLLUTION

The phrase "pollutant source" refers to both the place and the mechanism through which the pollutant enters the environment. Sources are normally described in terms of locations and source strengths (i.e., rates of pollutant emission). In the study of indoor air pollution this procedure for characterizing sources applies well to indoor-generated pollutants. It presents problems in discussing sources of outdoor-generated pollutants. The original sources of such pollutants may be far from the indoor environment of concern; e.g., sulfur dioxide from distant power plants, or photochemical oxidants arising in the open atmosphere impacted by automobile emissions.

The original source of an outdoor-generated pollutant is often beyond the scope of interest of indoor air pollution research. The researcher looks upon the ambient air as it enters the building as the proximate "source" of pollution. From the standpoint of an observer in a building, the sources of outdoor-generated pollution experienced within the building are the windows, doors, ventilation system intake ducts, and areas of unplanned leakage in the building envelope. In the discussion of outdoor-generated pollutants which follows, it is assumed that the effective "source" of the pollutant is the mechanism (ventilation or infiltration) through which the pollutant enters the building. The presence of outdoor pollutants within buildings has often been examined, in scientific research, in terms of the relation between indoor and outdoor pollutant concentrations. The definition of an "emission rate" at the point of entrance into the building has not often been attempted.

Two important reports of a previous literature search [65, 283]* prepared by Benson, Henderson, and Caldwell of EPA in 1972 and 1973, concluded on the basis of a broad literature review that, "except for bacteria and perhaps for fungus spores, indoor pollution levels appear to be controlled primarily by outdoor concentrations." The review did not neglect the role played by indoor pollutant generation; its broad conclusion refers to the dominant role of outdoor pollution as evidenced in the scientific literature available at that time. Benson et al. noted that many other factors influence indoor air pollution levels, among them internal activities and pollutant generation, atmospheric conditions and ventilation, time, location, type of building and air conditioning and filtration systems. They found that relative indoor concentrations of pollen and reactive gases decrease with increasing outdoor concentrations, and that the same effect can be observed, with less certainty, for particulates and non-reactive gases; but they cautioned against assuming indoor concentrations of these latter to be less than outdoor concentrations. Their conclusions were that the indoor-outdoor relationships are far from simple and that the amount of reliable and readily comparable data upon which to make generalizations is highly limited [65, 283].

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* The numbers in square brackets, here and on all following pages, refer to the bibliography in Appendix B. References are listed there in an order which is alphabetical and numerical.

The present document owes a large debt to the work of Benson and his associates. Their work has been drawn upon heavily. In general, where they have covered a subject in detail, the treatment here is very brief. The present document provides detail in indoor-outdoor air pollutant source and behavior research principally upon work reported after 1972 and hence not covered in their review. The reader is referred to the work of Benson and his associates for detailed discussions of work covered there.

There have been subsequent overviews of the indoor-outdoor air pollution problem, a major recent one being an Arthur D. Little report in 1976 on the environmental impacts of the new American Society of Heating and Refrigeration Engineers Standard 90-75 for energy conservation in new building design [44]. The Arthur D. Little report reconfirms the accepted view that outdoor air quality is a primary determinant of indoor air quality. One result of this general view of the indoor air pollution problem appears to have been that outdoor-generated pollutants have received the most study in indoor air quality research. Another result has been a continuing emphasis upon studies of indoor-outdoor pollutant concentration ratios.

A review of research into the outdoor-generated component of indoor air pollution follows, categorized by major pollutant species.

3.1.1 Sulfur Dioxide and Sulfates

Sulfur dioxide (SO_2) has been widely studied in indoor environments, as described in the following pages. No reports were found of studies in which sulfate concentrations have been measured in an indoor, nonworkplace environment.

The literature indicates that indoor SO_2 concentrations are primarily the result of the introduction of outdoor-generated SO_2 into buildings. There are few literature references to indoor generation of SO_2, although it has been demonstrated to occur in heating systems burning coal or oil [715, 69] and from gas stoves [308].

Typically, indoor concentrations of SO_2 are found to be a function of the SO_2 concentrations occurring outdoors, with the indoor concentrations generally lower than the outdoor concentration [65]. Two factors were reported as having a primary effect in producing lower concentrations of SO_2 indoors [65]. First, SO_2 is reactive and may be differentially absorbed by the interior walls, ceilings, floors, and their interior surfaces and finishes [704, 113, 590, 588, 551, 589, 250]. Second, the rapid rise and fall which characterizes outdoor peak concentrations of SO_2 are not reflected in similarly high, acute indoor SO_2 concentrations [492]. This reduction of peak values is the result of the mixing of outdoor air with indoor air as the peak SO_2 levels enter the building and diffuse within it.

In their 1972 literature review Benson, Anderson and Caldwell state that indoor SO_2 concentrations are roughly equivalent to outdoor concentrations when the latter are low. As outdoor SO_2 concentrations rise toward 20 pphm indoor SO_2 concentrations rise at a lower rate, reaching only about 50 percent of outdoor levels. When outdoor SO_2 concentrations rise above 20 pphm, the indoor-outdoor concentration ratio becomes still lower, with indoor concentrations being only about 30 percent of outdoor levels [65]. Many investigations have confirmed the general conclusion that when outdoor SO_2 concentrations rise indoor concentrations rise also, but at a slower rate and to lower maximum levels.

A series of investigations, beginning in 1958 and continuing to 1976, which demonstrate this are listed in Appendix B [492, 359, 69, 694, 681, 680, 433, 478, 243, 670, 712, 27, 308]. Table 1, adapted from a similar table prepared by Anderson in 1972 [27], displays the results of these investigators' findings of indoor-outdoor ratios. The table offers a convenient comparison among findings of various researchers, but care must be taken in interpreting results from such a display. Indoor-outdoor ratios of SO_2 may be expected to vary with the type of building and with its climatological exposure as well as with the absolute levels of ambient outdoor SO_2 outside the building. It would be desirable in such a table to stipulate absolute values of the concentrations, expressed in terms of a common, standard averaging period for measurements (24 hours for example) to permit verification of the conclusion, by Benson et al. [66], that the ratio drops with higher outdoor concentrations. Differences in room sizes, building materials, fixtures, furniture, ventilation rates, and occupancy probably also account for the differences among indoor-outdoor ratios found by investigators [27]. Of the studies made prior to 1973, only two measured ventilation rates [694, 415].

Anderson's own work in Arhus, Denmark in 1969 and 1970 [27], cited in Table 1, is illustrative as an example of indoor-outdoor SO_2 ratio studies. In this work the presence of SO_2 was demonstrated in 100 samples of outdoor air and 67 samples of indoor air. Sample values below 20 $\mu g/m^3$ (0.7 pphm) were omitted, when either indoor or outdoor air concentrations below that level were recorded, yielding the 11 pairs of simultaneous outdoor and indoor samples referred to in Figure 1. The author felt that the location was not ideal for the experiment, and that a higher outdoor pollution level would have been preferable for this investigation. His linear regression analysis of the 11 samples gave a coefficient of correlation $r = 0.52$ and a line of regression: $y = 0.20x + 20.9$.

TABLE I. AVERAGE INDOOR/OUTDOOR RATIOS OF SULFUR DIOXIDE (SO_2) AS MEASURED IN BUILDINGS BY VARIOUS INVESTIGATORS

Authors	Year of Investigation	Country & Town	Indoor/ Outdoor Ratio	No. of Days with Paired Samples	Sampling Periods
Kruglikova and Efimova	1954 - 1955	U. S. S. R. Moscow	0.48	58	24 h
Shephard et al.	1956	U. S. A. Cincinnati	~ 1.00	60	6 h
Phair et al.	1957	U. S. A. Cincinnati	0.64	60	2 h
Weatherly	1960	Great Britain London	0.60	12	24 h
Biersteker et al.	1964	Holland Rotterdam	0.20	800	24 h
Mizoguchi et al.	1965	Japan Tokyo	~ 1.00	Not Stated	Not Stated
Padfield	1965	Great Britain London	0.40	16	24 h
Gölfe	1965 - 1966	Germany Hamburg	0.20	~20	Continuous
Wilson	1968	Great Britain London	.25 - 1.00	10	--
Von Ulrich	19[illegible]	Sweden Stockholm	0.60	16	Continuous
Yocom et al.	1969	U. S. A. Hartford	~ 1.00	18	5 min.
Andersen	1969 - 1970	Denmark Århus	0.[illegible]	11	24 h
Hollowell et al.	1975	U. S. A. Berkeley Albany, Calif.	~1.00	--	Continuous

Notes 1. Table has been reproduced (with minor emendations) from I. Andersen in Atmos. Environmental, Vol. 6, 275-278, 1972.

2. Citations for the original authors listed here appear in an attached bibliography.

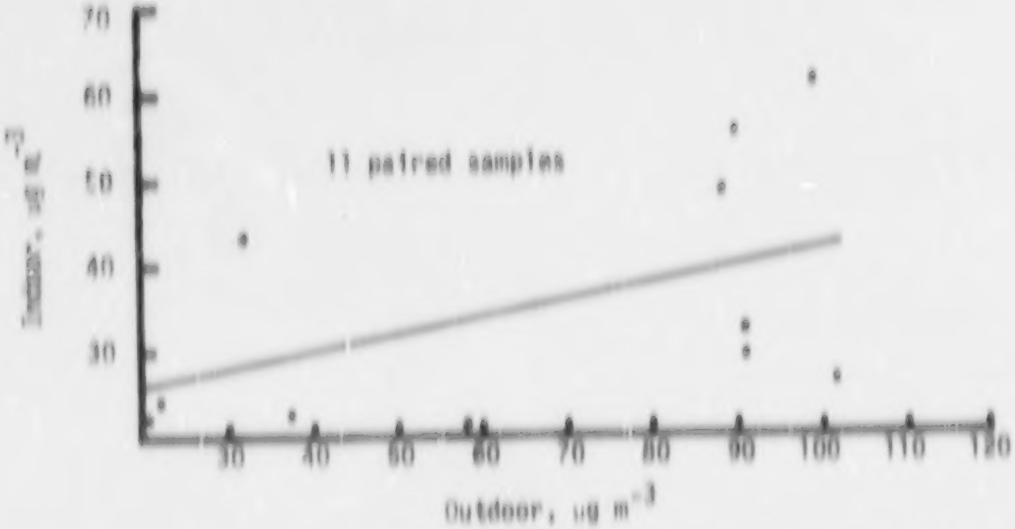

Figure 1. Scatter diagram of relationship between simultaneous 24-hour averages of indoor and outdoor sulfur dioxide on one locality. The line of regression is shown as it appeared in the original publication[27].

In another study of indoor-outdoor SO_2 levels, not recorded by Anderson in Table 1, Arthur D. Little Inc. conducted a field measurement program in air conditioned spaces in Boston and Cambridge, Massachusetts [42, 43]. The Arthur D. Little investigators, working in summer months, found that the indoor SO_2 levels were only slightly less than outdoor levels when the outside ambient air was between 3.5 to 5 pphm. As the levels of SO_2 outdoors rose above 5 pphm, the indoor SO_2 concentrations remained near their "normal" levels (normal was undefined by the author). When the SO_2 concentration outdoors dropped below 3.5 pphm, the indoor concentrations usually also dropped below 3.5 pphm. However, for one period of several days, the outdoor concentrations were on the order of 4 pphm while concentrations indoors for similar averaging periods were about 5 pphm. This was the only reported case in which indoor concentrations were higher than outdoor, although the results were presented graphically and average concentrations were not given. During the winter, when outside ambient SO_2 levels were higher, the indoor-outdoor ratio became lower as the outdoor SO_2 concentrations increased [65].

A study which specifically addressed seasonal and diurnal trends in indoor-outdoor SO_2 concentration ratios was conducted in Hartford, Connecticut in 1969 by TRC - The Research Corporation of New England [713]. Tables 2 and 3 were drawn from the TRC study. A Sign-X Model 604-13 conductimetric SO_2 analyzer was used in this study. The four sampling points were sampled sequentially on a 5-minute basis. The results show a wide variation, with several surprising examples of indoor-outdoor SO_2 ratios substantially higher than 1. In the case of the houses shown in Table 3, the high indoor concentrations were attributed to internal generation of SO_2 in a coal-fired furnace [714]. For the most part, the results of the TRC study confirm A.D. Little's finding that indoor-outdoor SO_2 concentration ratios are lower in winter than in summer.

TABLE 2. SULFUR DIOXIDE SEASONAL AVERAGES (PPHM) AND DAY-NIGHT RATIOS AT FOUR PUBLIC AND OFFICE BUILDINGS IN HARTFORD, CONNECTICUT [713]

	LIBRARY			CITY HALL			[illegible] CONSTITUTION PLAZA			[illegible] CONSTITUTION PLAZA		
	Day	Night	Ratio Day/Night	Day	Night	Ratio Day/Night	Day	Night	Ratio Day/Night	Day	Night	Ratio Day/Night
FALL:												
Far Outside	0.6	1.1	0.51	1.7	2.2	0.77	1.7	1.8	0.94	0.3	.2	1.5
Near Outside	1.0	1.9	0.53	2.5	2.4	1.04	2.3	2.1	1.10	0.1	.2	0.5
Near Inside	1.0	2.2	0.45	2.4	2.7	0.89	1.3	1.1	1.18	-0.2	-0.1	-
Far Inside	1.2	2.7	0.44	2.0	2.5	0.80	1.4	1.0	1.40	-0.3	-0.1	-
Far Inside / Far Outside	2.0	2.45		1.18	1.14		0.82	0.56		-		
WINTER:												
Far Outside	6.1	7.6	0.81	6.8	7.1	0.96	5.3	5.2	1.02	4.5	3.7	1.22
Near Outside	6.6	7.8	0.85	7.2	7.4	0.97	5.0	5.8	0.86	4.7	4.1	1.15
Near Inside	6.1	7.7	0.79	6.1	5.7	1.07	4.0	4.3	0.93	3.9	3.5	1.11
Far Inside	6.0	7.3	0.82	5.8	5.6	1.04	3.9	4.0	0.98	3.8	3.7	1.03
Far Inside / Far Outside	0.98	0.96		0.85	0.79		0.73	0.77		0.84	1.00	

Note: Average concentrations of SO_2 are stated in pphm and are derived as averages of a series of 24 hour SO_2 readings taken throughout the Fall and Winter seasons, respectively.

TABLE 3. SULFUR DIOXIDE SEASONAL AVERAGES (PPHM) AND DAY-NIGHT RATIOS AT TWO HOUSES IN HARTFORD, CONNECTICUT [713]

	Blinn St.			[illegible] Rd.		
	Day	Night	Ratio Day/Night	Day	Night	Ratio Day/Night
SUMMER:						
Far Outside	0.6	0.1	6	0.3	0.5	0
Near Outside	0.9	0.3	3	0.8	1.0	0.8
Near Inside	1.7	0.4	4.25	5.3	2.8	1.87
Far Inside	1.[illegible]	0.5	3.0	3.6	2.5	1.50
Far Inside / Far Outside	3.5	1.67		[illegible]	5.5	
FALL:						
Far Outside	3.5	6.0	0.60	3.2	3.5	0.95
Near Outside	3.5	3.6	0.97	2.4	2.6	1.00
Near Inside	3.1	1.6	0.65	2.1	0.2	10.5
Far Inside	1.9	2.5	0.76	2.0	0.6	3.3
Far Inside / Far Outside	0.56	0.42		0.61	0.25	
WINTER:						
Far Outside	1.5	2.1	0.72	1.3	1.7	0.76
Near Outside	1.3	2.3	0.56	1.3	1.9	0.68
Near Inside	1.1	1.6	0.69	0.8	0.4	2.0
Far Inside	1.0	1.7	0.59	0.6	0.1	6.0
Far Inside / Far Outside	0.77	0.81		0.46	0.06	

As noted, the high SO_2 levels in the Blinn Street residence, shown in Table 3, were attributed by Yocom to SO_2 generation in a furnace in the building. This, and other references to indoor generation of SO_2, will be returned to later in this report under the headings of Section 3.2, Indoor-Generated Pollutants and Section 4.0, Distribution and Behavior of Indoor Air Pollution.

A useful study of the contribution of outdoor ambient SO_2 to indoor air pollution is included in research recently reported by the Lawrence Berkeley Laboratory [308] in which a survey was conducted of six homes with gas and electric cooling and gas heating appliances, in order to characterize the indoor air quality and determine the level of gaseous and aerosol air pollutants from typical indoor combustion sources. Field measurements of SO_2 were made continuously both indoors and outdoors using a Thermo Electron 43 instrument which monitors SO_2 by UV fluorescence. Results are discussed subsequently in Section 3.2 under Indoor Generation of Air Pollution.

3.1.2 Carbon Monoxide

The literature review conducted in 1972 by Benson and his associates concluded that carbon monoxide (CO) concentration levels appear to follow a pattern similar to SO_2 concentrations [65]. Indoor concentrations of CO ranged from 80 to 100 percent of outdoor concentrations when outdoor concentrations were below 10 ppm. They ranged from 60 to 80 percent of outdoor concentrations when outdoor concentrations were above 10 ppm. The authors noted that carbon monoxide is relatively unreactive. It should not behave like SO_2 by being absorbed on the surfaces of walls, ceilings, or floor coverings, and its indoor concentrations should therefore approximate the outdoor concentrations when monitored over a period of time. No explanations were suggested by Benson and his associates for the observed reductions of indoor CO levels below the outdoor levels.

One of the studies referenced by Benson and his associates was performed in Hartford, Connecticut by Yocom, Clink and Cote [71]. Figure 2 and Table 4 display results of this study.

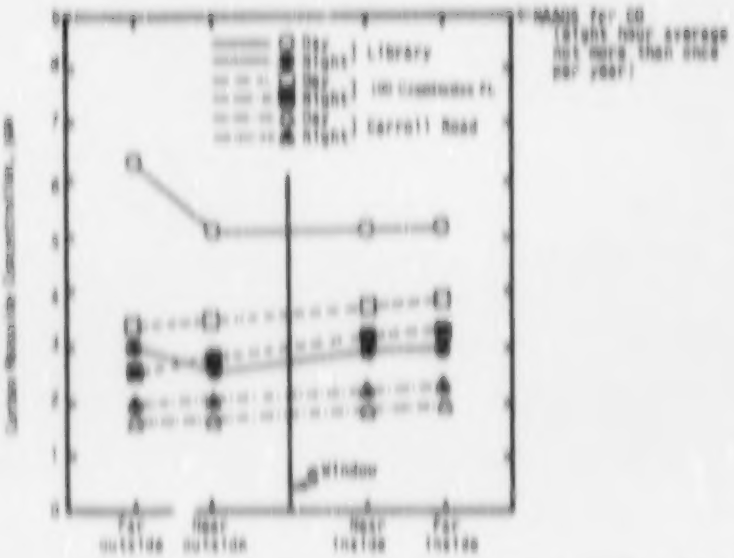

Figure 3. Indoor/outdoor profile for winter CO data in Hartford, Connecticut. [711]

TABLE 4. SUMMARY OF CARBON MONOXIDE RESULTS, PPM (INDOOR/OUTDOOR RATIO, DIMENSIONLESS)

	Location	Sample Site	Summer		Fall		Winter	
			Day	Night	Day	Night	Day	Night
Offices and Public Buildings	Library	Far Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Far Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Indoor/Outdoor	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	City Hall	Far Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Far Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Indoor/Outdoor	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	100 Constitution Plaza	Far Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Far Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Indoor/Outdoor	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	200 Constitution Plaza	Far Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Far Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Indoor/Outdoor	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Residences	[illegible]	Far Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Far Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Indoor/Outdoor	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Carroll Road	Far Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Outside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Near Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Far Inside	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Indoor/Outdoor	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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Note: These tables were reproduced from an article by Messrs. Yocom, Clink, and Cote published in the *Journal of the Air Pollution Control Association*, Vol. 21, No. 5, 1971. Averaging times were not given although the monitoring methodology is described. Five minute samples were directed sequentially to an Intertech Infra-2 NDIR spectrophotometer. [711]

In these observations the indoor-outdoor CO concentrations ratio varies from a low value of 0.76 to a high value of 1.32, clustering around unity. There is not a clear tendency for the value to be significantly below unity.

Benson and his associates [65] cited indoor-outdoor CO concentration ratios obtained in living quarters in the vicinity of two Russian industrial plants by Skvortsova [575] in which outdoor concentrations were above 10 ppm and the corresponding indoor levels were substantially lower. Other studies of carbon monoxide impact on indoor air quality arising from exterior sources of carbon monoxide, cited by Benson and his associates, involved monitoring indoor levels of CO in dwellings near known outdoor sources. Among these were studies by Lampert [367] and Berdyev et al. [66]. These studies of indoor-outdoor CO concentrations in circumstances of elevated outdoor CO levels generally indicate that indoor CO levels do not increase as rapidly as outdoor levels. The results are not conclusive and suggest a need for further studies of indoor CO concentrations when outdoor CO levels are 100 ppm or above.

Several studies have examined the special case of "air rights" buildings, in which buildings for residential and public use are constructed directly over heavily travelled roadways. The question of carbon monoxide pollution penetration into buildings - the carbon monoxide originating in motor vehicle exhaust - becomes of special interest in this type of building.

One such study, involving measurement of indoor-outdoor air quality and traffic relationships at two buildings in New York City, was conducted by the General Electric Company for EPA and published in 1972 [233]. Five Intertech NDIR CO instruments were used by the General Electric team of investigators. High concentrations of ambient carbon monoxide at three monitoring locations at one of the buildings, referred to as the "air rights site," were expected since that building was an air rights, high rise apartment dwelling straddling the heavily travelled, multilane Cross-Bronx Expressway. The other building, referred to as the "canyon site," was a similar high-rise apartment dwelling but was not an air rights building; air quality measurements at the canyon site were taken for control and comparison.

The General Electric Company investigators concluded that the primary influences on the outdoor-indoor relationships of the four pollutants monitored (i.e., carbon monoxide, hydrocarbon, total particulates and lead) were:

- Traffic conditions
- Nontraffic-related sources
- Meteorological conditions
- Site configuration.

Specifically for carbon monoxide concentrations observed, the General Electric Company investigators concluded:

- Carbon monoxide concentrations at all outdoor and indoor locations result from automotive emissions on roadways in the site vicinity.
- On-roadway concentration levels increase linearly with increase in traffic flow rate and decrease with traffic velocity.

- CO concentration gradients across a roadway vary as a function of traffic conditions in all lanes of the road and the wind conditions close to the road.

- CO concentration gradients from a roadway to a building vary as a function of the horizontal distance and the road level wind direction between the high volume traffic lanes and the building. Winds from the high volume lanes to the building increase concentrations at the building.

- Average CO concentrations at the base of the building vary directly with average concentrations of CO on the roadway but are lower in proportion to increases in horizontal and vertical distances from road level. These distances create finite response time lags at the building to changes in traffic concentrations which vary as a function of road level wind speed, direction and turbulence.

- There is an appreciable reduction in both peak and average carbon monoxide levels between "on-roadway" locations and adjacent buildings at the air rights site, but not at the canyon site. As a result there is no significant difference in CO levels along the outside walls and inside the two structures.

- Concentrations indoors at the building base in both buildings vary with outdoor concentrations. Indoor concentrations lag changes in outdoor CO levels. It is suspected that this time delay is a function of both wind conditions as seen at the building and the direction of change in outdoor concentrations.

- Average concentrations inside and outside the buildings reduce exponentially with height above ground level. The rate of change with height outdoors is essentially the same in the heating and nonheating seasons. However, indoors the decay in average concentrations with height is greater during the nonheating season than during the heating season. This variation is the result of changes in the roof wind angle from the nonheating to the heating season.

- Indoor concentrations normally are lower than outdoor concentrations at all heights above the roadway when outdoor concentrations are high. Conversely, indoor concentrations are higher than outdoor concentrations when outdoor concentrations are low [233].

These nine conclusions offer explanations for variations in indoor-outdoor CO concentrations in terms of the four influences listed previously, i.e., traffic conditions, nontraffic-related sources, meteorological conditions, and site configuration.

The TRC study by Yocom, Clink and Cote cited earlier [715] produced similar results for a different air rights building. The Hartford Public Library straddles a busy four-lane access road connecting downtown Hartford with a major interstate highway. Indoor CO concentrations at this library approximated near-outside concentrations (i.e., CO levels adjacent to outside walls of the structure) but were lower than far-outside concentrations when the far-outside concentrations were high. The terms near-inside, far-inside, near-outside and far-outside refer to sampling points close to or at some distance (unspecified) from the wall.

The studies cited above deal with CO as an outdoor-generated pollutant. Other studies dealing with indoor CO pollution resulting from indoor generation (incomplete combustion in gas stoves, for example) will be described in Section 3.2, Indoor-Generated Pollutants.

3.1.3 Carbon Dioxide

Carbon dioxide (CO_2) is a normal constituent of the atmosphere occurring in unpolluted ambient air in concentrations ranging from 310 to 330 ppm. Pollution of outdoor air with anthropogenic CO_2, resulting primarily from combustion of fuels, may result in ambient CO_2 concentrations as high as 700 ppm. Average background ambient CO_2 levels have risen over the last 100 years, from about 290 to above 325 ppm [394]. There has been concern over the yearly additions of CO_2 to global background concentrations because CO_2 in the atmosphere absorbs terrestrial long-wave radiation (heat energy) and re-radiates it back to earth. The effect of an increased amount of CO_2 in the atmosphere is to reduce the rate of cooling of the earth's surface and, in theory, will lead to an increase in the earth's surface temperature (greenhouse effect) [12].

Local ambient concentrations of CO_2 higher than background levels are regularly produced as a result of the emission of CO_2 from industrial combustion processes. High levels of CO_2 have thus been used as an indicator of polluted air [557], but such concentrations, ranging up to 700 ppm, do not appear to have been of concern as an outdoor pollutant infiltrating into indoor environments. CO_2 is generated not only by a complete combustion of carbonaceous fuels used in heating and cooking but also in human expiration and smoking; it is therefore a commonly indoor-generated pollutant, but a review of the literature suggests that its indoor source strengths have been little studied.

Researchers have found that carbon dioxide concentrations in enclosed spaces can be dramatically higher than in the ambient air. Ishido [326] reported that concentrations in several types of office buildings ranged from 1 to over 10 times outdoor levels. Further, according to Ishido, a space of 10 cubic meters (m^3) per person and a recirculation rate of 30 m^3/hr are required to maintain CO_2 concentrations below 0.1 percent in rooms where people are doing office work.

Other investigators have examined carbon dioxide concentrations indoors, finding higher concentrations indoors than out [65]. Studies have been made of carbon dioxide generation in submarines and space craft [530, 479, 661].

3.1.4 Nitrogen Oxides and Nitrates

Only within the last four years have there been investigations of the indoor-outdoor relationships of the nitrogen oxides, NO and NO_2. Studies previous to 1972 of nitrogen oxides in the indoor environment were stated by Benson and his associates to have been insufficient for identifying the indoor-outdoor relationships [65]. No studies of nitrate formation in or entrance into nonworkplace environments were found in the literature search for the present report.

As is the case with SO_2 and CO, the nitrogen oxides may be generated outside the building or within it. Researchers have studied both aspects of nitrogen oxides in buildings. The present discussion focuses on outdoor sources but the two categories of sources cannot be wholly separated. Additional information on indoor generation of nitrogen oxides appears in Section 4.4.

The sparse literature of indoor-outdoor nitrogen oxide concentrations does not show the pattern of reduced indoor levels found for SO_2 and CO in similar situations. For example, in a study conducted in Dushambe, USSR, on the effect of motor vehicle exhaust gases on air quality in dwellings, investigators found that concentrations of nitrogen oxides were the same in the street as in the first and third stories of the houses monitored nearby [66]. In another case comparisons made between indoor and outdoor air at several locations in Tokyo including factories, business machine rooms and offices yielded no significant differences between indoor and outdoor NO_2 concentrations [433].

In a study of indoor-generated pollutants by TRC at four private residences in Hartford, NO and NO_2 were monitored at several locations within the dwellings and outside them using a Bendix Chemiluminescent NO/NO_x Analyzer [143]. Unlike earlier studies in Hartford by the same group of investigators, indoor-outdoor ratios of monitored pollutants were not reported, since the purpose of this more recent program was to investigate the indoor generation of air pollutants. The authors stated no general conclusions pertaining to the ratio of indoor and outdoor nitrogen oxides concentrations except in discussions of results of each separate dwelling. In general, however, nitrogen oxides concentrations were reported to be lower outdoors than at all locations indoors owing to the presence of an indoor nitrogen oxides source, the gas stove [143].

Derham [158] conducted an investigation of indoor and outdoor concentrations of nitrogen oxides in a building near Los Angeles. Although the building was not close to any heavily travelled roads, the report stated that "peak concentrations seemed to be related to 'rush hour' traffic." Results of this study were reported graphically for each monitored pollutant, with concentrations by time of day for selected days. Further discussion of the results and conclusions of this study will appear in Section 4.4 since the thrust of the work centered on the indoor behavior of this pollutant.

Thompson and others [627] monitored NO, NO_2 and oxidants outside and inside 11 buildings in the South Coast Basin of California during summer and fall seasons. Nitrogen oxides were grab sampled in mylar bags and brought to a laboratory where they were monitored by "Atlas electric devices, NO_2 - NO_x analyzers." Concentrations of nitrogen oxides were found to be lower inside than outside although the indoor-outdoor differences were less than with the more-reactive oxidants. Nitrogen oxide levels inside elementary and high school classrooms without air conditioning were found to be essentially the same as levels of nitrogen oxides outside the buildings.

The study of nitrogen oxide monitoring by the Lawrence Berkeley Laboratory [308] will be discussed under Section 4.4 with indoor-generated pollutants, since this was the thrust of that investigation.

4.1.5 Photochemical Oxidants

Photochemical oxidants are secondary pollutants formed in photochemical smog from reactions involving hydrocarbons and oxides of nitrogen. The principal component in this category is ozone (O_3) [557]. The presence of significant amounts of ozone in the indoor environment is usually the result of its infiltration from the outside [439, 534, 627].

Indoor and outdoor concentrations of ozone were measured for three air-conditioned offices in Boston and Cambridge during the 1968 air-conditioning season by the Arthur D. Little Company. A follow-up study was conducted during the heating season. In general, the investigators found that ozone levels indoors were not much lower than those found outdoors. The O_3 levels were much less in the winter heating season, since O_3 is photochemically generated most strongly during the summer, but the differences between indoor and outdoor concentrations were slight in both seasons [42, 43]. These results are contrary to what might logically be expected to take place in the transfer of ozone to the indoor environment. Since O_3 is a strong oxidizing agent reacting with other gases (for example, with NO to form NO_2) reactions with NO and with various materials within the building would have been expected to deplete the O_3 rapidly. Subsequent studies have validated these results for offices using outside air for ventilation, but show variant results for other types of buildings [627, 439, 534].

In a study conducted in 1971 by researchers at California Institute of Technology [534] comparisons were made between the indoor and outdoor O_3 levels in Pasadena, a city known for its high O_3 concentrations. The first purpose of the investigation was to monitor outdoor and indoor ozone levels at a typical private residence and at two adjacent campus laboratory and office buildings. Both campus buildings were air-conditioned but one was supplied with 100 percent outside air while the other was supplied with 70 percent outside air and 30 percent recycled exhaust air. A second purpose of the investigation was to investigate the mechanism through which ozone decays. Measurements of the rate of ozone decomposition were recorded. Air filters were tested with respect to their effectiveness in destroying ozone and, finally, a theoretical model was developed to permit the correlation of indoor versus outdoor concentrations of ozone as a function of time [534]. Within the office building which utilized 100 percent outside air, peak ozone concentration values were found to be about 80 percent ± 10 percent of the outside values monitored at an APCD (Air Pollution Control District, County of Los Angeles) station, located roughly 500 feet from the two buildings. Within the adjacent office building, where 30 percent of the air was recycled, the peak ozone levels were about 65 percent ± 10 percent of the peak outside levels measured at the APCD station. At the private residence the ventilation system was left off; windows were open and the doors were opened periodically as persons entered and left the dwelling. Instantaneous measurements of outdoor and indoor O_3 concentrations indicated that the maximum indoor concentrations of O_3 were about 70 percent those of the outside, and that these maxima lagged those of the outside by about one hour. Further, the researchers found that the ozone level within a home decreases at rather rapid rates once the doors and windows are closed [534]. Specifics concerning mechanisms of ozone decay and the development of a ventilation model for relating indoor-outdoor ozone concentrations will be discussed later in this report under Section 4.0, Distribution and Behavior of Indoor Air Pollutants and Section 9.0, Modeling of Indoor Air Pollution respectively.

A group of investigators from Major Appliance Laboratories, General Electric Company, conducted experiments on the decomposition rate of ozone in several industrial facilities, an office and a home. Although this study will be reported in more detail in Section 4.0, Distribution and Behavior of Indoor Air Pollutants, it is worth noting here that the rate of ozone decay was found to be dramatically altered by variations in humidity or temperature and that the half-life of ozone in a typical bedroom was rather short (6 minutes). The authors concluded that ozone decomposes rapidly after it enters typical living spaces [439].

In an independent study conducted in Cincinnati, investigators concluded that ozone levels in a closed residence are significantly lower than the normal range of outdoor ozone concentrations. Thompson [627] attempted to determine the relationship between the concentrations of six major pollutants (total oxidant, PAN, NO_2, NO, CO, and particulate matter) in the ambient air and the concentrations of those pollutants to which people were exposed in hospitals located in Riverside, California. Total oxidant was monitored using a portable Mast ozone meter. Within specific structures, the relative concentration of total oxidant depended primarily upon the rate at which it entered the building. Of the six pollutants studied, ozone decomposed at the fastest rate [627].

3.1.6 Hydrocarbons

The outdoor-generated hydrocarbon of principal interest is the total class of nonmethane hydrocarbons for which a National Ambient Air Quality Standard has been established. There have been few studies of the penetration of outdoor-generated hydrocarbons into indoor environments; those which have been conducted, however, indicate that the indoor concentrations of hydrocarbons are directly proportional to the density of automobile traffic in proximity to the indoor locations [614, 233].

Hydrocarbons may enter a building as an outdoor-generated pollutant (as implied by the studies cited above) or as an indoor-generated pollutant from household chemicals, solvents, fuels and other consumer-product sources. These indoor-generated categories will be considered in Section 3.2.

Hydrocarbons and their derivatives are usually divided into two broad classes: aliphatic hydrocarbons, the chained compounds and those cyclic compounds which resemble the open-chain compounds; and aromatic hydrocarbons, benzene and the compounds that resemble benzene in chemical behavior. Polynuclear aromatic hydrocarbons are those hydrocarbons in which two or more aromatic rings fuse and share a pair of carbon atoms.

Polycyclic organic matter consists of compounds with two or more rings that share two or more carbon atoms including aromatic hydrocarbons, cyclic aliphatic compounds, and the aliphatic-aromatic compounds. All of these may occur in the total class of nonmethane hydrocarbons and may enter buildings as outdoor-generated pollutants. Given the task to produce a background document on polycyclic organic matter pollution, a panel of the National Academy of Sciences - National Research Council chose to divide this broad area into two studies: Particulate Polycyclic Organic Matter (POM) [459] and Vapor-Phase Organic Pollutants [460]. Since the latter study was broad in scope in the sense that both cyclic and noncyclic compounds were of concern, the document treated materials with low vapor pressure and high molecular weight only briefly. Since these documents are not in themselves original research, reports of studies described in these documents which pertain to contamination of the indoor environment required primary document assessment and are cited herein (when referred to) under the original investigations.

The contamination of indoor air with concentrations of polynuclear aromatic hydrocarbons (PAH or PNA) may be the result of either indoor generation, primarily smoking, or the infiltration of ambient air which contains PAH. Bridbord et al. [87] reported indoor concentrations of benzo(a)pyrene (BAP) ranging from 0.0011 to 0.150 $\mu g/m^3$. BAP is an important constitutent of the polynuclear aromatics, is a known carcinogen, and is often used as an index compound for PAH concentrations. BAP concentrations in the ambient air are primarily the result of motor vehicle emissions, heat and power generation, coke production and refuse burning

[87]. Ambient levels of BAP have been found to range from 75-78 $\mu g/m^3$ near bituminous paving operations (averaging times were unavailable) [87].

Data have been collected in office sites (with the absence of tobacco smoke) that suggest that indoor air is 25-70 percent lower in POM concentrations than air found in the immediate outdoor environment [459]. Detailed information on smoking behavior in these indoor spaces, however, was unavailable.

Thompson [627] monitored PAN (peroxyacetyl nitrate, a chemically reactive outdoor-generated member of the photochemical hydrocarbon complex) using a PAN analyzer monitoring instrument in 11 buildings on the south coast basin of California. The author found that PAN concentrations varied in a similar fashion to those of ozone but that because of its greater stability it persists inside structures much longer.

3.1.7 Particulates

Particulate matter has been measured both in the indoor and outdoor environments using a wide variety of techniques and is reported under a number of names (e.g., total suspended particulate, particulate matter, smoke, dust counts, inorganic and organic particulate, dirt, soiling index, and respirable particulate). The lack of standardization in research terminology and technique makes it difficult to compare many of the important results and conclusions of experiments undertaken to characterize particulate indoor-outdoor relationships.

One study by Anderson [27], however, included a review of previous indoor-outdoor particulate sampling, as shown in Table 5. In the work cited by Anderson, it appears that when particulate measurements are taken for one-hour averaging periods the ratio of indoor to outdoor concentrations of suspended particulate matter is about 0.40 [564, 241]. Experiments in which 24-hour samples were taken, however, reported indoor-outdoor ratios of 0.80 to 0.95 [580, 478, 69]. In his own experiment Anderson collected 150 paired samples of suspended particulate matter, measured simultaneously at distances one meter inside and one meter outside a room in the technical school of Arhus, Denmark. Figure 3 is a scatter diagram of the results of his experiment. The correlation coefficient was 0.[illegible] and his calculated line of regression was y = 0.63 x + 5.9. In 69 percent of his paired samples the indoor particulate concentrations were lower than the outdoor concentrations. Anderson concluded that the reduction in suspended particulate matter was presumably due to differences in the outdoor and indoor settling, diffusion, and coagulation processes [27].

TABLE 5. AVERAGE INDOOR/OUTDOOR RATIOS OF SUSPENDED PARTICULATE MATTER (SPM) [27]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		
[illegible]	[illegible]	[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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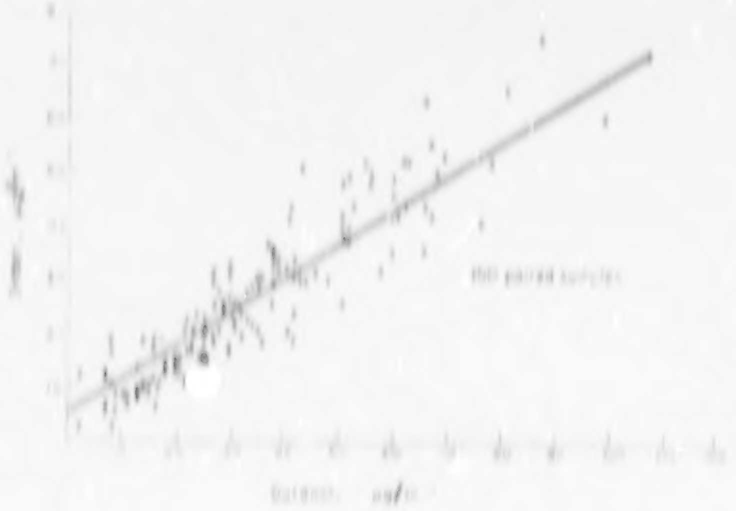

Figure 1. Scatter diagram of relationship between simultaneous 24-hour averages of indoor and outdoor suspended particulate matter in one locality (the line of regression is shown) [87].

Studies in Japan concluded that indoor suspended particulate levels are completely under the influence of outdoor changes [324, 325]. Thompson and his associates [527] stated that the greater part of the large-sized particulate matter carried into schools and other buildings in the South Coast Basin of California consists of soil particles brought in on shoes.

In a study in Hartford, Connecticut, by Yocom and others, investigators found that the daytime concentrations of particulate are higher than nighttime levels by as much as 100 percent. The Hartford group found that for offices and other public buildings, indoor day-night ratios are lower than outdoor day-night ratios in both summer and winter. Another way of putting this is to say that the concentration of particulates in the air inside an office building does not drop relatively as much at night as does the concentration of particulates in the immediately adjacent outside air. For dwellings, the opposite was true. Particulate levels within dwellings dropped relatively more at night than did the particulate levels in adjacent outdoor air [65, 712].

The studies cited above have dealt with simple mass concentrations of particulate matter per unit volume. These are of interest for indoor air quality considerations, but it also of importance to study the size distribution, other physical chararteristics and chemical characteristics of indoor air pollutants. Characterization of the size of suspended particulate is important since the health hazard is related to the fraction of particulate which can enter the human respiratory tract. Particles larger than about 4 μm typically do not pass the nasopharyngeal portion of the upper respiratory tract and are therefore of less health hazard. Respirable particulates have been defined by the American Conference of Governmental Industrial Hygienists [16] as those which pass through a size selector with the following characteristics:

Aerodynamic Diameter (unit density sphere) (μm)	Particles Passing Through Size Selector (Percent)
2.0	90
2.5	70
3.5	50
5.0	25
10.0	0

In the course of the Hartford study of particulates an effort was made to obtain an indication of the relative concentrations of both respirable particulates and total suspended particulates, indoors and outdoors, during the summer season. Unfortunately, however, the monitoring methodology proposed was found to be unreliable by the investigators and their sponsors and was therefore abandoned [713].

Concentrations of lead in the air and household dust were studied in Omaha, Nebraska by Angle and McIntire [33]. They reported lead levels of up to 1.69 $\mu g/m^3$ in a grade school located next to a battery fabrication plant; lower levels were reported at urban and suburban high schools. House dust lead concentrations were measured in urban and suburban homes and day care centers. The urban samples ranged from 50 to 1200 $\mu g/gm$ of dust while the suburban samples ranged from 110 to 610 $\mu g/gm$ [33]. Sayre et al. [539] reported that lead in house dust may be higher than 5 $\mu g/gm$ and contribute significantly to the blood level of lead in children.

3.1.8 Other Outdoor-Generated Pollutants

Other outdoor-generated pollutants monitored with respect to indoor-outdoor concentration ratios in nonworkplace environments were reported in studies by Tomson and others of carbon disulfide and hydrogen sulfide [631], monitored at a house near a viscose plant which discharged these gases into the air; and "gaseous acids" as reported by Phair and others [492]. Studies of indoor-outdoor ratios of pollens and other biological aerosols are found in the literature; these typically show, when the aerosols orginate outside the building, that their concentrations indoors are at lower levels than outdoors. Such studies have been more commonly performed for hospital and laboratory rather than residential environments [146, 595]. The noncriteria pollutants (i.e., pollutants other than the six - SO_2, CO, NO_x, oxidants, nonmethane hydrocarbons, and particulates - for which National Ambient Air Quality Standards have been set) have, however, been principally studied in indoor environments as indoor-generated pollutants.

3.2 INDOOR-GENERATED POLLUTANTS

The discussion of outdoor-generated pollutants in Section 3.1 was categorized by pollutant species, all pollutants having come effectively from a single source - the outdoor ambient air. The discussion of indoor-generated pollutants will be categorized by their sources in the indoor environment: these are combustion, household cleaning and maintenance, smoking, hobbies, aerosol spray products, and other sources.

3.2.1 Combustion

Two principal combustion sources of pollutants in buildings are the heating plant and the stove. Other possible sources of combustion-related pollutants are fireplaces, automobile operation in attached garages, and candles.

3.2.1.1 Building Heating Plant Contributions

Building heating plants may be sources of CO, CO_2, NO, NO_2 and SO_2, as well as particulates, any of which might be discharged into indoor environments through faulty venting or operation of the heating plant. Studies demonstrating the existence of such discharges are rare.

In a study conducted on 60 houses heated with oil, coal or gas in Rotterdam, Netherlands, Biersteker and his associates concluded that indoor SO_2 concentrations are not significantly affected by the heating system used if the system is in good condition, but they reported that indoor concentrations of SO_2 were 3.8 times the outdoor levels for a 30 year-old home where a heater was believed to be faulty. They noted that newer homes tend to have less sulfur dioxide in the living rooms than older homes, and they concluded from their data that faulty chimneys and heaters may play a bigger role in air pollution mortality than has thus far been suspected [69]. It was noted by Yocom and his associates in their study of sulfur dioxide indoor-outdoor concentrations at two houses in Hartford, Connecticut that a coal-fired furnace was the probable source of indoor levels of SO_2 exceeding simultaneous outdoor levels by a factor of as much as 2.5 [713]. In neither the Biersteker nor the Yocom studies were any actual source strength measurements attempted for the indoor pollution arising from heating plants.

In a recent study by the Lawrence Laboratory, elevated nitrogen oxide levels were reported in a house equipped with a gas furnace [308], but reports of NO and NO_2 levels associated with gas-fired heating plants are rare; Benson and his associates found none in their 1972 literature review. In this respect it is to be noted that Yocom et al. [716] reported that gas heating systems did not appear to affect indoor CO concentrations.

The possibility that chrysotile asbestos dust may be emitted into indoor environments from rotary asbestos heat exchangers was cited by Tonomura et al. [631] who reported concentrations from this source of 0.52 fibers/liter, well below a recommended maximum standard of 2 fibers/liter.

3.2.1.2 Gas Stoves and Ovens

A comprehensive study of the impact of gas stoves on indoor air quality was conducted by TRC in 1973 and 1974 [143]. The study included two tasks:

- Laboratory Study - measured emissions of NO, NO_2 and CO from normally used and operated gas stoves in relation to several operating variables. Concentrations on a mass basis were monitored in a completely enclosed laboratory structure using a stove selected as being representative. The operating variables evaluated included air-fuel ratios, flame intensity, time and temperature and the use of pilot lights.
- Field Study - measured indoor and outdoor concentrations of NO, NO_2 and CO continuously over two-week periods in four homes with gas stoves. This study was conducted in Hartford, Connecticut during two separate field measurement programs during the spring-summer of 1973 and fall-winter of 1973-1974. Three sampling points were located indoors (one or two in the kitchen and either the living room or bedroom) and one was located outdoors. Data on stove use was recorded by the homeowner.

Table 6 is a summary of the results of the laboratory program. For comparison, the authors included in the table emissions from a domestic gas

TABLE 6. SUMMARY OF POLLUTANT EMISSIONS OF GAS APPLIANCES FOR SEVERAL TYPICAL OPERATING CONDITIONS IN HARTFORD DWELLINGS [148]

Appliance	Operation	Heat Input Rate (Kcal/Hr)	Pollutant Emission Factors (µg/Kcal)			Pollutant Emission Rates mg/Hr		
			NO	NO_2	CO	NO	NO_2	CO
Older Gas Stove with Cast Iron Burners	Pilot Lights 1 Burner - High Flame 3 Burners - High Flame	150 2700 6780	45.3 92.6 117.0	54.6 51.8 72.8	419 382 475	6.8 250.0 793.0	8.2 140.0 494.0	62.9 1031.0 3220.0
	Oven: Transient Steady-state	 2300 2200	 157.0 91.4	 159.0 73.1	 1790 530	 361.0 201.0	 366.0 161.0	 4117.0 1166.0
	Broiler: Transient Steady-state	 3000 3800	 137.0 88.8	 123.0 48.5	 1350 976	 411.0 337.0	 369.0 184.0	 4050.0 3708.0
Newer Gas Stove with Pressed Steel Burners	Pilot Lights 1 Burner - High Flame 3 Burners - High Flame	100 3500 10200	4.7 130.0 138.0	18.6 79.0 65.6	842 510 315	0.5 455.0 1408.0	1.9 277.0 669.0	84.2 1785.0 3213.0
	Oven: Transient Steady-state	 4000 2200	 331.0 77.9	 79.0 50.4	 1010 1620	 1324.0 171.0	 316.0 111.0	 4040.0 3564.0
	Broiler: Transient Steady-state	 4900 3700	 126.0 136.0	 80.6 57.1	 846 757	 617.0 503.0	 395.0 211.0	 4145.0 2800.0
Unvented Space Heater	Low Flame-Steady-state High Flame-Steady-state	2800 6200	76.4 135.0	46.4 43.8	632 319	214.0 837.0	130.0 272.0	1770.0 1978.0
Domestic Gas Furnace*	————	Approx 30000		90.0	36		2700.0	1080.0

* From Compilation of Air Pollution Emission Factors (Revised), U.S. EPA, February 1972.

furnace. From the laboratory study the authors concluded that:

- The type of gas stoves tested emit significant quantities of oxides of nitrogen and carbon monoxides in the following ranges depending upon stove operation:

  NO = 90 - 130 μg/Kcal, 200-1000 mg/Hr
  NO_2 = 50 - 80 μg/Kcal, 100-500 mg/Hr
  CO = 400 - 1000 μg/Kcal, 1000-4000 mg/Hr

- Pollutant emissions from the newer stove were not consistently higher or lower than the older stove for the range of operations evaluated. The oven of the newer stove did emit about three times more CO than the older stove oven.

- The different designs of the burners of the two stoves did not appear to have consistent and reproducible effects upon pollutant emissions. Tests designed to evaluate the effect of air-fuel mixture upon burner operation indicated that the best blue luminous flame was produced at an intermediate air shutter opening for each stove. Variation in the shutter opening had little effect on the pollutant emissions for the older stove but had a greater effect on the newer stove. The intermediate air shutter opening (best flame) also had the highest oxides of nitrogen levels for the newer stove.

- Pilot lights, although using gas at a small rate, do contribute quantities of pollutants comparable to those generated during cooking operations over a typical 24-hour period because of their continuous nature. Pilot light NO and NO_2 emissions from the newer stove were less and CO emissions higher than those from the older stove. The newer stove also has a pilot light designed to use less gas than the older stove.

- Evaluation of the number of burners in use and their flame intensity showed that the emissions are similar for all conditions when adjusted to an equivalent heat input basis. Oven and broiler emissions are somewhat less than those for the burners on the same heat input basis. An exception was the larger amount of CO from the oven of the newer stove.
- Total pollutant emissions per unit of time from a gas stove are roughly proportional to the number and type of burners used and the period of use [143].

The TRC group tested several representative types of utensils on one burner of each stove. The types of utensils, flame settings and concentrations are shown in Table 7. The most substantial utensil effect apparent is higher CO concentrations from the use of the aluminum pot at low flame conditions.

TABLE 7. POLLUTANT CONCENTRATIONS[a] RELATED TO VARIOUS UTENSILS

Test	Operating Conditions	Utensil	Stove	Pollutant Concentrations, µg/m³		
				NO	NO_2	CO
	Low Flame:		New			
18A		Aluminum		27	59	1088
18B		Cast Iron		32	66	585
18C		Stainless Steel		33	72	832
18D		Pyrex		[illegible]	76	474
18E		None		27	62	675
	High Flame:		New			
19A		Aluminum		180	208	1910
19B		Cast Iron		221	224	1831
19C		Stainless Steel		[illegible]	[illegible]	2180
19D		Pyrex		233	224	2080
19E		None		237	158	2180

[a] The effect of utensils on pollutant generation was determined by measurement of pollutant concentrations directly above the stove rather than by calculation of pollutant quantities entering and leaving the laboratory enclosure [143].

Based upon the findings of the field study the Hartford group concluded:

- Stove use and outdoor air quality both influence indoor air quality. This joint influence is a function of house permeability as determined by season. No evidence could be found that stove and house age per se influenced indoor air quality. Except for CO in House No. 2, concentrations of CO, NO and NO_2 are higher indoors than outdoors.

- The patterns of indoor air quality are influenced by interior design features. Kitchen concentrations are always higher than other locations in the house where sampling takes place.

- Indoor NO_2 concentrations in the kitchens of most of the houses are at concentrations which would exceed the National Ambient Air Quality Standard for NO_2 of 100 $\mu g/m^3$ annual average (if the concentrations were projected over one year.) On several occasions, a concentration of 100 $\mu g/m^3$ is approached or exceeded throughout the house. In fact, average kitchen NO_2 concentrations for most sampling periods were two to four times the outdoor NO_2 concentrations.

- Indoor CO concentrations during the winter at House No. 3 and No. 4 approached the 8-hour average air quality standard for CO of 10,000 $\mu g/m^3$ (10 mg/m^3 or 9 ppm).

- The half life of CO, an extremely unreactive gas, was found to be 2.1 hours in House No. 2 during an unoccupied period. The half life for NO was 1.8 hours indicating its relatively high stability in the indoor atmosphere. On the other hand, NO_2 had a half-life of 0.6 hours indicating that in addition to dispersion and dilution, NO_2 disappears through reaction, absorption, or adsorption. This effect was noted in a qualitative way in several of the other houses.

- Stove pilot lights were found to be a significant source of NO_2 [143].

Findings by the Hartford group differ somewhat from findings of Eaton and others at EPA [178]. This group, studying indoor air pollution in a home using a gas stove, found significantly higher indoor kitchen concentrations of NO_2 than did the Hartford group. Eaton and his associates found peak values of NO_2 of 1 ppm (≈ 1880 μg/m^3) with one-hour averages ranging from 0.25 to 0.50 ppm (≈ 470 to 940 μg/m^3) when the kitchen was closed with no ventilation; the gas flow was 0.204 ft ^{3}/min, and the sampling intake was 6 feet from the stove. Comparisons of indoor CO concentrations observed by these two groups show more similarity, however, although the EPA group found significantly lower CO concentrations. Most probably the difference in CO concentrations may be explained by the difference in sampling distance from the stove. The Hartford group sampled above the stove and "in the kitchen, displaced somewhat from the stove" [308]. The difference in NO_2 concentrations would require more careful comparisons in technique, averaging time and instrumentation for a valid comparison of results.

Most recently "pilot measurements" of SO_2, $NO/NO_2/NO_x$, O_3 and CO were taken at various locations in and out of doors by a team of investigators from the Lawrence Berkeley Laboratory of the University of California. Indoor measurements were taken in kitchens with the measurements being made in the breathing zone approximately 1.5 meters above the floor near the front of the stove [264]. Table 8 shows levels observed by this group in three houses with the gas oven operating at 550° F for approximately 20 minutes.

TABLE 8. GASEOUS AIR POLLUTANTS OBSERVED IN HOMES WITH GAS OVENS (OBSERVED LEVELS ± 15%)

Home ID Number	2		3	5
Ventilation Conditions	No Duct Fan Off	No Duct Fan On	Duct No Fan	Duct No Fan
CO (μg/m^3)	23,000	6,000	2,000	7,000
NO (μg/m^3)	2,000	1,000	500	150
NO_2 (μg/m^3)	850	320	150	95
SO_2 (μg/m^3)	110	65	< 25	< 15

(reproduced from Hollowell et al. 1976 [308])

The reference to "duct" in this table is to a duct leading from the kitchen to the outside air - House Nos. 3 and 5 were equipped with ducts of this kind, but had no kitchen exhaust fans. House No. 2 had no kitchen duct but was equipped with a kitchen exhaust fan; tests were made in House No. 2 with the fan on and with the fan off.

Table 9, also from Hollowell et al. [308], shows the effects upon pollutant concentrations in the breathing zone under various conditions of operations of the top burners of a gas stove. These researchers also found a small increase in ozone levels during the use of an electric stove.

TABLE 9. EFFECT OF GAS BURNER CONDITIONS ON GASEOUS EMISSIONS
(OBSERVED LEVELS ± 15%)

Home Identification Number	Pollutant	Kitchen Background	One Burner On No Grate	One Burner On With Grate	One Burner On With Grate and All Stainless Steel Pan
2	CO	9,000	10,000	7,000	27,000
	NO	85	1,050	1,110	740
	NO_2	85	380	380	370
	SO_2	40	65	90	80
3	CO	1,000	2,000	3,000	13,000
	NO	25	165	125	180
	NO_2	30	115	65	125
	SO_2	<15	25	<15	<15
4	CO	3,000	4,000	3,000	3,000
	NO	55	1,110	1,230	680
	NO_2	60	450	470	360
	SO_2	<15	40	35	25
5	CO	6,000	8,500	9,000	8,000
	NO	75	1,260	990	640
	NO_2	50	340	320	265
	SO_2	25	50	70	25

(reproduced from Hollowell et al. [308])

The purpose of these separate works was to measure the emissions of gas-fired appliances and to test and propose methodologies for NO_x reduction.

Comparisons of the various studies of $NO/NO_2/NO_x$ and CO emissions and concentrations must be made with great care. While the different experiments described here have carefully documented the various operating parameters which are controlled or allowed to vary in the respective studies, each experiment used different sampling point locations, gas fired-appliances, air-fuel ratios, and so forth. A more detailed examination of each of the studies and their respective operating parameters must be made before comparative tables or graphs of experimental results may be made. One such comparative task was displayed in a recent work by A.D. Little, Inc. and is reproduced in Table 10 [44].

TABLE 10. GAS KITCHEN AND OUTDOOR CONCENTRATIONS OF NO_2 AND CO

(Indoor, μg/m³/Outdoor, μg/m³)

Reference	NO_2 (24-hour average)	CO (8-hour average)
Melia (average of 31 summer samples and 70 winter samples in 171 kitchens)	133/68	a
Melia (average of 59 winter samples in 59 kitchens)	108/38	-
Cote (average of 14-18 winter days of monitoring in 3 kitchens)	87/42	2000/1800

[a] One hour CO average of 27 winter samples in 27 kitchens during cooking was 5100 μg/m³ ± 1100 μg/m³.

3.2.1.3 Candles With Lead Wire Core Wicks

The burning of candles with wicks containing lead wire cores will contribute lead fumes and particulates to indoor air. Bridbord and Shy [85] reported on both chamber and home experiments. In the chamber study, a lead-wicked candle was burned in an 1.5 m^3 chamber with an airflow of 0.54 m^3 per hour. The level of lead in the chamber air was reported to average about 850 $\mu g/m^3$ for the four hours that the candle was burned.

The investigators found an average airborne lead concentration of approximately 10 $\mu g/m^3$ as a result of the burning of lead-wicked candles in a home. As a result of these experiments the investigators concluded that "... it would not be unreasonable to expect average indoor air lead levels in the range of 10-20 $\mu g/m^3$ as a result of regularly burning candles with lead wire core wicks in the home" [85].

3.2.2 Household Cleaning and Maintenance

Household cleaning and maintenance can impact upon indoor air quality through mechanical action and through the entrance into the air of cleaning and maintanance materials as pollutants themselves. In the first category, mechanical action, household cleaning and maintenance remove some particulate matter from indoor surfaces which could otherwise become later reentrained and airborne. But household cleaning and maintenance also put particulates (e.g., dust) into the air and may result in the generation of gaseous pollutants (from solvents, for example) and aerosol pollutants from the cleansers. As an example of the adverse mechanical impact of cleaning, suspended particulate matter concentrations indoors by weight, as well as by particle counts, were shown by Annis and Annis [34] in 1973 to increase during the just after vacuuming.

Manoharan et al. [411] found that 73 percent of the particles in indoor air were below one micron in size. These small particles are transported by the air medium in which they are suspended (i.e., subject to Brownian movement, streamline flow, etc.). Sweeping, dusting, and vacuuming can resuspend small particles held on the floor or carpet; in vacuuming many of these small particles pass directly through the vacuum bag.

Solvents and aerosols used in cleaning process are themselves contaminants in the indoor environment. Their impact may be localized to the specific rooms in which they are applied but, nevertheless, they can enter the respiratory system during the process as evidenced by the ability of the occupants to detect their odor. A detailed inventory of the contents of common solvents and aerosols used for cleaning and the exposures to building occupants of any of the active ingredients has not been studied in a substantive manner.

Cote and his associates in 1974 listed the active ingredients for several household cleaning products. Furniture polish often contains silicone, wax, and morpholine. Window cleaners often contain sodium nitrate, isopropyl alcohol, ethylene glycol, and ammonium hydroxide. Oven cleaners contain relatively reactive species as evidenced by the ease in which organic materials break down on the surfaces of ovens and stoves; some of the ingredients are potassium hydroxide, hydroxyethyl cellulose, and polyoxyelthylene fatty ethers [143].

Air fresheners are also a source of indoor gaseous contaminations through introduction of substances to remove or mask household odors. Fennelly [208] points out that particulates are involved to some extent in odor transmission; they themselves are volatile, or may simply serve as a transport medium for volatile matter. The reduction of particulates has been shown to reduce odors from food preparation [64]. It has been found [74] that many air fresheners simply contain scents for which the nose is more highly sensitive than it is to the undesirable odor, as well as containing substances that reduce the nose's ability to detect odors. It is by this mechanism that most air fresheners mask odors rather than by reduction of particle counts, since large concentrations of spray or mist would be required to cause small particulates to coalesce. Cote et al. [143] report that the typical active ingredients of air fresheners consist of propylene glycol, morpholine, and ethanol. Triisopropanolamine and morpholine are often also contained in disinfectant sprays.

Solvents used in the cleaning process at schools and public buildings often contain higher concentrations of more active ingredients than those used in the household. Exposures to these substances, however, are usually localized and confined to cleaning personnel. Many dust mop dressings and sprays, as well as floor waxes and furniture polishes, release petroleum distillates during application. Hueper reported in 1962 that the distillation products of petroleum have been recognized as carcinogens on the skin and in the respiratory and alimentary systems. Further, many waxes and polishes utilize either turpentine, chloroform or carbon tetrachloride as a base to keep the product in a liquid form. Hueper noted that fumes which result from the evaporation of the base are chloroform and carbon tetrachloride which have been shown to be potential carcinogens. The many common cleansers, detergents, and scouring powders which use chlorine as a bleaching agent release fumes containing chlorine gas. The maximum allowable concentration of chlorine gas for an eight-hour exposure in industry is 1 ppm, the level at which chlorine can be detected by smell is usually in the range of 3-4 ppm [571]. In addition, the use of dichlorobenzene compounds to mask odors in toilet rooms results in its release as a gas [571]. The use in cleaning procedures of solvents which include the aromatic, chlorinated and aliphatic hydrocarbons, as well as esters, ketones, acids, and alkalis may present a potential air pollution problem [403]. Blume has noted that the many products which are commonly used to "cleanup," therefore, may actually contribute significantly to the deterioration of the air in the indoor environment of schools and homes [74].

Building maintenance projects are often a source of indoor air pollution. Sawing and sanding of wood introduce particulates (sawdust) into the air. Blume has reported that pine, birch, mahogany and beechwood when used as indoor paneling can elict allergic reactions in some individuals, presumably from emanation of airborne allergens although Blume is not explicit about the transfer mechanism [74]. The use of asbestos or fiberglass insulating or tiling materials can introduce asbestos and fiberglass into the air. The use of paint, varnish, shellac and lauquer introduces contaminants in the air which affect not only the user but also occupants of rooms freshly painted; the principal pollutant is the solvent [494].

The polychlorinated biphenyls (PCB's), which are used as plasticizers in some paints, may evaporate and be present in the air [353]. PCB's are also used in varnishes and floor tile and, therefore, may present a similar problem in this context [622]. The diphenyl mercury dodecenyl succinate used in latex paint to prevent fungal growth can result in the release of mercury vapor. The application of latex paint in rooms with poor circulation can lead to mercury levels which exceed recommendations of the American Conference of Governmental Industrial Hygienists (ACGIH) [570]. It was also found that the mercury vapors will remain in the air for a considerable period, being present at 1000 times the ambient outdoor levels 220 hours after application [570].

3.2.3 Smoking

The combustion of tobacco products is a source of air contamination which is solely a function of human habit and decision. The health effects of tobacco smoke for the smoker have long been studied, but the effects of tobacco smoke on indoor air environment and upon non-smokers in indoor environments have only recently been the subject of investigation. The inhalation of tobacco smoke involuntarily, by persons who are not actively smoking, has been defined by Hoegg as passive smoking; this term is widely used in current literature to describe the circumstance of breathing air contaminated with tobacco smoke [531, 546, 132, 270].

Tobacco smoke contains a large number of chemicals. Stedman [601] reported that "the number of compounds in the vapor particle phase exceeds 1,200" including: acids; alkanes; alkynes; alkenes; aldehydes; alcohols;

alkaloids (one of which is nicotine); aromatic hydrocarbons; arsenic; carbon dioxide; carbon monoxide; cadmium; carbohydrates; chromium; hydrogen cyanide; esters, ketones; nitrogen dioxide; nitric oxide; nitric cyclic ethers; oxygenated isoprenoid compounds; phenols, phenolic ethers; polycyclic hydrocarbons including benzo(a)pyrene and benzanthracene; nickel; radioactive constituents; steroles; sulfur compounds, and fat soluble and insoluble particles of 'tar' [601, 351]. Tobacco smoke has also been found to contain toxins which may be produced by bacteria and fungi present during the curing and storage of tobacco [218, 578]. The smoker's exposure to these chemicals results principally from mainstream smoke which is the smoke inhaled directly into the smoker's lungs. The sidestream smoke, which is not directly inhaled during smoking, is the major tobacco smoke contributor to indoor air pollution, since it has been found to contain higher concentrations of tobacco smoke components than the mainstream smoke [341, 675]. Kilburn reports that, "sidestream smoke contains greater quantities of chloroform, extractable tar, nicotine, pyrene and cadmium" [351]. Rylander found that sidestream smoke contained almost double the amount of benzo(a)pyrene than mainstream smoke [533].

A table displaying a comparison of the quantities of various components of mainstream and sidestream cigarette smoke, based upon data from Hoegg [303] and Corn [141] appears in the *Health Consequences of Smoking* published by the U.S. Department of Health Education and Welfare in 1975 [657].

	Compound	Mainstream (mg/cig)	Sidestream (mg/cig)	Ratio Sidestream/ Mainstream	Comment
A	General characteristics				
	Duration of smoke production	20 sec	550 sec	27	
	Tobacco burnt	347	411	1.2	
	Particulates, no. per cigarette	1.05×10^{12}	3.5×10^{12}	3.3	
B	Particulate phase				
	[b]Tar (chloroform extract)	20.8	44.1	2.1	
		10.2	34.5	3.4	Filter Cig.
	Nicotine	0.92	1.69	1.8	
		0.46	1.27	2.8	Filter Cig.
	Benzo(a)pyrene	3.5×10^{-5}	13.5×10^{-5}	3.7	
	Pyrene	13×10^{-5}	39×10^{-5}	3.0	
	Total phenols	0.228	0.603	2.6	
	Cadmium	12.5×10^{-5}	45×10^{-5}	3.6	
C	Gases and vapors				
	Water	7.5	298	39.7	3.5 mg of Mainstream and 5.5 mg of Sidestream to particulate phase, rest to vapor phase
	Ammonia	0.16	7.4	46	
	Carbon monoxide	31.4	148	4.7	
	Carbon dioxide	63.5	79.5	1.3	
	Oxides of nitrogen	0.014	0.051	3.6	

The quantities shown in this table are estimated for a 35 ml puff volume, 2 sec. puff duration, one puff per minute and 23 or 30 mm butt length and 10 percent tobacco moisture.

Another table from an earlier HEW report on The Health Consequences of Smoking, published in 1972 [653], provides lists of cigarette smoke compounds which were judged to be probable or suspected contributors to the health hazards of smoking. Those lists were as follows:

Compounds in cigarette smoke judged as probable contributors to the health hazards of smoking.

Compound	Concentration in cigarette smoke micrograms/cigarette	Primary phase classification G-gas P-particulate
Acrolein	45-140	G
Cresol (all isomers)	68-97	P
Hydrocyanic Acid	100-400	G
Nitric Oxide	0-600	G
Nitrogen Dioxide	0-10	G
Phenol	9-200	P
Acetaldehyde	180-1,440	G
Acetone	86-650	G
Acetonitrile	140-200	G
Acrylonitrile	10-15	G
Ammonia	60-330	G
Benzene	12-100	G
1,3-Butadiene	41-200	G
Butylamine	3	P
Carbon Dioxide	23,100-78,300	G
Crotononitrile	8	G
Dimethylamine	10-11	P
DDT	0-0.77	P
Endrin	0.08	P
Ethylamine	10-21	G
Formaldehyde	20-41	G
Furfural	45-110	P
Hydrogen Sulphide	12-35	G
Hydroquinone	83	P
Methacrolein	9-11	G
Methyl Alcohol	80-300	G
Methylamine	10-23	G
Nickel compounds	0-3.14	P
Pyridine	25-215	P

In the document from which these lists were taken [65] there were references to specific scientific investigations to support the suggested health hazards involved.

As the above lists show, the products of tobacco combustion include a wide range of gaseous and particulate contaminants. Tar and nicotine are often selected from these as the substances used to characterize the relative productions of toxic pollutants in smoking. Tar refers to the amount of particulate produced corrected for water vapor. Nicotine, an alkaloid, is the largest particulate product; it is known to be highly toxic. Its presence in the air results only from the combustion of tobacco and of related plant products; it is therefore a useful indicator of the presence of tobacco combustion products in indoor air pollution monitoring programs.

Studies of passive smoking have also used suspended particulate matter (SPM), smoke, and carbon monoxide to characterize indoor contamination. A more detailed treatment of tobacco smoke concentrations and behavior is discussed in Section 4.0, Distribution and Behavior of Indoor Air Pollutants.

3.2.4 Hobbies

The types and kinds of hobbies individuals pursue govern to a large extent their potential indoor exposures to toxic air contaminants. Many hobbies include activities involving toxic materials which, in an occupational environment, would be controlled through protective measures such as hood ventilation. These controls may be absent in the home environment. This is particularly true of such activities as soldering and furniture refinishing.

Painting in the home requires the use of a variety of solvents and pigments, many of which are potentially quite hazardous. Oil paints, oil varnishes, and resins (containing solvent bases consisting of aliphatic, aromatic and halogenated hydrocarbons, alcohols, ketones and esters, or mixtures of these categories of compounds) release toxic fumes during drying processes (which involve oxidation and polymerization reactions) [650].

Artists may use pigments in powder form which consist of very fine dust in the respirable particulate size range. These pigments consist of a powdering base and a metallic element which utilize lead, arsenic, antimony, cadmium, chromium, manganese, or mercury (to name a few) to give the pigments their characteristic colors. Paint removers that contain methylene chloride (also known as dichloromethane) can result in high concentrations of carboxyhemoglobin because of the rapid metabolization of methylene chloride to carbon monoxide [610, 611]. Varnishes and wood stains used in such hobbies as furniture refinishing contain various toxic solvents such as turpentine and the esters and ketones used in lacquers. The inhalation of silica dust, which can lead to silicosis [273, 50], is a potential hazard in ceramics and sculpturing. The inhalation of fumes which result from the firing of pottery is hazardous because of the presence of toxic metals, fluorine, chlorine, and sulfur dioxide gas. The presence of asbestos in soapstone and serpentine is also a concern in sculpture because of the potential for inhalation of asbestos dust [273, 50]. McCann has noted that solder, used in hobbies such as the making of leaded glass objects, can produce vapors containing cadmium. Hobbies which involves the use of plastics (acrylics, polyesters, epoxy resins, polyurethanes, vinyl polymers, and polystyrenes) can also result in exposure to toxic gases as they are heated to make them pliable. Some hobbies involve using acrylic sheets and blocks while others use acrylic glues and cements. The cements are either pure solvents like methylene chloride, ethylene dichloride, and trichloroethane, or acrylic chips which are dissolved in those solvents. The polyester resins which are used in laminating consist of nontoxic polyesters dissolved in a styrene monomer to which methyl ethyl ketone peroxide or benzoyl peroxide is added. Epoxy resins produce large amounts of heat during the curing process and can result in the production of toxic amine fumes from the hardener. The highly toxic polyurethanes are made of isocyanate and polyols and the spray foam and is considered too toxic for casual use, although these products may be purchased at most hobby shops. The vinyl polymers which include polyvinyl chloride and polyvinyl acetate can release hydrogen chloride fumes. The cutting or sawing of polystyrene when heated will produce methyl chloride gas, also highly toxic [403].

The various printmaking processes such as silk screening, etching, lithography, and the photo techniques involved with each, as well as photographic processing, involve exposure to air contaminants. The solvents used in silk screening contain several toxic vapors such as xylol, methyl ethyl ketone and acetates. The fumes from the nitric and hydrochloric acids used in etching and lithography are also hazardous. Photo techniques which require use of carbon arcs as a lighting source produce carbon monoxide, nitrogen oxides, ozone, and toxic metal fumes. The development of film requires the use of solutions which can give off toxic vapors containing sodium hydroxide, sodium sulfite, formaldehyde and chlorinated hydrocarbons. The fumes from acetic, hydrochloric, and chromic acids which are used in most photographic processes are also hazardous. The result of the mixing of sodium sulfite and acetic acid, commonly used in the photographic fixer, produces sulfur dioxide. If the most common reducer, which contains potassium ferricyanide, is exposed to heat or concentrated acids in a photo workshop, hydrogen cyanide gas can be produced [403].

3.2.5 Aerosol Spray Products

Aerosol spray products, although varying widely in the chemical nature of the pollutants they put into the indoor air, may be appropriately considered as a general category of pollutant source because of their quite similar source emission characteristics. Their periods of emission are brief, are wholly controllable, and are the direct result of conscious human activity within the building.

Cote et al. [143] conducted a survey of aerosol sprays used among TRC employees and attempted to quantify them as a source of indoor air contamination. They noted in their survey the usage rates, location of use and the frequency of time of use of each aerosol spray product. Most aerosol spray systems consist of a small amount of active ingredients and a propellant. The active ingredients vary greatly in both concentration and contents. Many of the substances used are highly toxic to humans and are accompanied with specific directions and warnings to control misuse. All sprays contain a propellant used to dispense the functional or active portion from the container. It is estimated that 75 percent of the aerosol products contain one or more Freons as propellants [143]. Freon is a DuPont tradename for various halogenated hydrocarbons.

The halogenated hydrocarbons consist of one or more alkyl groups with one or more attached halogens, usually chlorine and fluorine. Other propellants are isobutane, propane, nitrous oxide, methylene chloride, and (in the past) vinyl chloride. Selikoff and Hammond reported that when vinyl chloride is used as a propellant it can lead to exposures that can exceed 100 ppm [560]. The discovery of a high incidence of angiosarcoma in workers who had been exposed to high concentrations of vinyl chloride led to the elimination of vinyl chloride as a propellant in aerosol sprays through an action of the Consumer Product Safety Commission in 1975. A list of active ingredients in aerosol sprays was provided by Cote et al. [143] and Frisch et al. [223]. Table 11 is a combination of these two lists.

In a report published in 1975, Gay [230] presented a similar list of propellants in aerosol products, by product category, which included the following:

Product classification	Propellants used
Inhalants containing bronchodilator drugs (11 products)	Freon 11 (trichlorofluoromethane) Freon 12 (dichlorofluoromethane) Freon 114 (dichlorotetrafluoroethane)
Mouth products (6 products)	Freon 12 Freon 114 Freon 142B (monochlorodifluoroethane)
Vaporizers (2 Products)	Freon 11 Freon 12 Trichloroethane

Product classification	Propellants used
Hair products (62 products)	Freon 11 Freon 12 Freon 114 Freon 152a (difluoroethane) Methylene chloride Vinyl chloride Propane Isobutane
Women's personal hygiene products (22 products)	Freon 11 Freon 12 Freon 114 Isobutane
Deodorants and anti-perspirants (38 products	Freon 11 Freon 12 Freon 114 Freon 142b Propane Isobutane
Foot products (9 products)	Freon 11 Freon 12 Freon 114
Miscellaneous products for personal use (18 products)	Freon 11 Freon 12 Freon 114 Isobutane Propane

Cote et al. [143] estimated emissions in the form of usage rates for the specific households surveyed. Since the exact proportions of propellants and active ingredients were proprietary information, data were unavailable on the exposure of individuals to any of the active ingredients contained in the sprays. Table 12 describes the aerosol usage patterns of persons surveyed in this study.

TABLE 11. ACTIVE INGREDIENTS IN COMMON AEROSOL SPRAY PRODUCT CLASSES [165, 255]

Housekeeping Products	
Furniture Polish	[illegible], 1,1,1-trichloroethane, petroleum distillates, silicones, wax emulsifiers
Spot Remover	Perchloroethylene
Oven Cleaner	Sodium hydroxide, hydroxyethyl cellulose, polyoxyethylene, fatty ethers
Drain Cleaner	1,1,1-trichloroethane, petroleum distillates
[illegible]	O-phenylphenol, N-alkyl-N-ethyl morpholinium ethyl sulfate
[illegible]	4-chloro-2-cyclopentylphenol, diethanolamide-lauric acid amide
Tile Cleaner	[illegible]
Pre-wash Treatment	Perchloroethylene, petroleum distillates
Window Cleaner	Sodium nitrite, isopropyl alcohol, ethylene glycol, ammonium hydroxide
Disinfectant Sprays	[illegible] morpholine
Air Fresheners	Propylene glycol, morpholine, ethanol
Personal Use	
Deodorant Spray	Hydrated aluminum chloride, isopropyl myristate talc, triglycerides
Hair Spray	Vinyl acetate copolymer resins, polyvinyl-pyrrolidone resins, ethanol, lanolin
Shaving Foams	Stearic acid, triethanol amine, menthol, glycerine
Paint Sprays	
Protective Coatings	Polyurethane
Stain	Hydrocarbons, ethers
Metallic Plating	Hydrocarbons, resins
High Temperature Coating	Hydrocarbons, resins
Craft Spray	Petroleum distillates
Glass Frosting	Toluol, xylol
Primers	Toluol
Adhesive	Petroleum distillates
Gloss	Toluol, xylol
Varnish	Petroleum distillates
Insecticides	
Wasp and Hornet	O-isopropoxyphenylmethyl carbamate, 2,2-dichlorovinyl dimethyl phosphate, petroleum distillates
Ant and Roach	Pyrethrins, piperonyl butoxide, n-octyl sulfoxide of isosafrole, petroleum distillates
Mosquito and Fly	Dicarboximide, petroleum distillates
Moth	Dicarboximide, petroleum distillates
House and Garden	Cyclopropane, petroleum distillates
General Insect	Toluamide
Garden Sprays	
Poison Ivy Control	Dichlorophenoxyacetic acid
Wilting Protector	Pinolene
Herbicide	Dichlorophenoxyacetic, propionic and benzoic acids
Pruning Paint	Asphalt solids, petroleum distillates
Pet Sprays	
Dog Repellent	Paradichlorobenzene
Cat Trainer	Paradichlorobenzene
Cat Flea Spray	[illegible]

TABLE 12. AEROSOL USAGE PATTERNS BY AEROSOL PRODUCT CATEGORY in TLC HOUSEHOLDS [140]

Product Category	Percentage of Households Using this Product	Frequency of Use	Time of Use	Location of Use	Average Usage Rate for Household g/mo.	Weight Fraction of Propellant Percent	Propellant Emission Estimates (g/wk)
Deodorant Spray	74	Once or Twice a Day	Early Morning; Late Evening	Bathroom	112-140	40	1.8-7.2
Hair Spray	71	7 times per week	Morning or Evening	Bathroom	84-112	70	4.9-6.5
Shaving Foam	45	Once a day	Morning or Evening	Bathroom	84-112	10	0.3-0.4
Air Fresheners	28	Once a week	Morning-Afternoon	Throughout House	28-56	80	5.6-11.2
Disinfectant Sprays	65	3 times per week	Morning-Afternoon	Kitchen, Bathroom	112	80	7.5
Furniture Polish Sprays	86	Once a week	Morning-Afternoon	Living Room, Bedrooms, Dining Room	56	60	8.4
Dust Sprays	18	Once a week	Morning-Afternoon	Living Room, Bedrooms, Dining Room	28-56	60	4.2-8.4
Oven Cleaners	42	4 times per year	Afternoon	Kitchen	84	10	20-25

Gay et al. [230] in an investigation of the exposure to vinyl chlorides, PVC's and other propellants, conducted an experiment to determine concentrations of these substances over time. The results found were as follows:

Concentration of propellant after 60-sec release
of hairspray and deodorants in 29,300 liter room.

Sample	Time,min	Propellant concentration, ppm Vinyl chloride	Freon 12
1	Breathing zone during spray	122.7	62.1
2	10	25.0	11.0
3	30	5.6	2.5
4	60	0.1	0.1

Concentration of propellant after 30-sec release
of insect spray in 21,400 liter room.

Sample	Time,min	Propellant concentration, ppm Vinyl chloride	Freon 12
1	1	380.1	466.4
2	31	62.1	54.4
3	61	24.6	26.4
4	151	10.3	11.5
5	151	0.8	0.9

3.2.6 Other Sources of Indoor-Generated Pollutants

3.2.6.1 Pesticides

Pesticides in the air are extremely hazardous because it is thought that the body is able to absorb pesticides faster and in greater quantities through the lungs than through either ingestion or skin contact [558]. The pesticides which are used most frequently in the indoor environment and therefore contribute the most to indoor air pollution are insucticides. Household insecticides comprise a large group of chemicals which number in the hundreds and include synthetic organic, inorganic and botanical chemicals. The synthetic organic chemicals contain the derivatives of chlorobenzene (i.e., DDT), indane (i.e., aldrin, dieldrin and chlordane, etc.), benzene hexachloride (i.e., lindane), chlorinated camphene (i.e., toxuphene), phosphate esters (i.e., malathion) and carbamates. The inorganic chemical-type insecticides use arsenic compounds, fluorides, selenium etc., while the insecticides from botanical sources include nicotine and pyrethrin [36]. The following table illustrates the many different types of active ingredients which are present in some of the most common brand name household insecticides.

Insucticide	Active Ingredient
Echols Roach Tablets	Boric Acid
Hot Shot Roach and Ant Bug Killer	d-trans Allethim
Johnson's No Roach	Malathion
Longlife Flea Killing Collars for Dogs	DDVP
Raid Ant and Roach Killer	DDVP
Raid Flying Insect Killer	Pyrethrins
Real Kill Insect Spray	Pyrethrins
Shell Improved No-Pest Strip	DDVP

In some cases the insecticide's effectiveness is increased by adding chemicals such a N-octyl bicyclopeptene dicarboxamide which has a synergistic effect on the d-trans allethrin in Hot Shot Roach and Ant Bug Killer [36]. Insecticides can cause problems associated with indoor air pollution primarily by two ways, through respiratory contact during use (e.g., aerosols) and through the inhalation of the products which result from the insecticide's volatilization [71]. Some insecticides, e.g., lindane, chlordane and DDVP, remain in the environment for long periods of time and may vaporize from surfaces long after application thereby releasing harmful chemicals to the air [139]. Many household insecticides are sold in aerosol cans, presenting health problems to the user during and shortly after their use. No reports of quantitative investigations of the pesticide persistence in the indoor air were identified in the literature search. Most pesticide studies have been concerned with pesticide use outdoors as monitored in soil and water.

The dispersion routes that pesticides take in the air have not yet been defined [594, 333, 624]. Very little is known of the products which result from the transformation of pesticides that takes place in the air [550, 566].

3.2.6.2 Air Conditioning Systems

Air conditioning systems can be a source of air contaminants of the indoor environment. The pollutants include biological aerosols, ozone, and particulates such as aluminum and asbestos dust. Air conditioners have been found to be a source of biological aerosols, that is, microorganisms have been found in and being distributed from air conditioners

[52, 313]. It has also been reported that air conditioners contribute to the levels of ozone in the indoor environment [313]. The authors just cited found that air conditioning systems have contributed to the generation of dust containing asbestos from wall spaces, where asbestos had been applied by spray, as an insulation material in the airducts of air conditioning systems. The contamination of air by aluminum compounds (hydrated aluminum oxide, chlorinated aluminum oxide, and carbonated aluminum oxide) was reported by Buchnea and Buchnea [94] and Horton [313] to result from the corrosion of the aluminum used in air conditioners.

3.2.6.3 Insulation Systems

Asbestos has been widely used in fabrics, insulation, ceiling tile, and fireproofing [488]. Damage to and erosion of such materials in buildings has been found to contribute to contamination of the air [467]. Asbestos dust was reported in air samples when spray-applied asbestos was used to coat wall spaces [313]. Spackling, patching and taping compounds used in some home repair work were found to contain asbestos and result in the exposure to dangerous concentrations in the indoor air [525]. Although Tanomura [632] found a lack of significant air contamination resulting from the use of asbestos in heat exchangers, Horton [313] points out that only light microscopy was used; the conclusion was not definitive. Rohl et al. [525] pointed out that light microscopy cannot allow for the individual study of particles in the 3μm range where the spackling, patching and taping compound particles normally are.

The study of asbestos contamination of air in public buildings conducted by Nicholson and others [467] included the reporting of measurements of asbestos fiber concentrations in the air in homes of asbestos workers. Concentration levels between 100 and 5,000 μg/m^3 were cited, but no information was provided about the circumstances of the measurements.

3.2.6.4 Particle Board

Formaldehyde is introduced into the indoor air environment from particle board, a building insulation and furniture material which is being used more and more frequently. Andersen et al. [29] reported in 1974 that formaldehyde concentrations in the air of 23 Danish homes ranged from 0.08 to 2.24 mg/m^3. It was found that the concentration of formaldehyde decreased with the age of the house (the newest had the highest concentrations) and with increases in ventilation rates.

3.2.6.5 Solvents

Indoor air concentrations of carbon tetrachloride have been measured in houses (near a solvent recovery plant in Maryland) at between 10-45 ppm while the outside ambient air contained 1 ppm [86]. The same investigator prepared a tabulation of predicted concentration levels of halogenated hydrocarbon solvents (a class of which carbon tetrachloride is a member), which is as follows:

Solvent	Temperature °C	Predicted indoor air concentration, ppm
Trichloroethylene	20	80
Tetrachloroethylene	26	26
1,1,2-Trichloroethane	21	26
1,1,1-Trichloroethane	20	130
Carbon Tetrachloride	23	130
Methylene chloride	24	520

The predicted indoor concentrations shown here are based upon the assumption that the solvents reach 0.1 percent of saturation levels [86], which is in effect an estimate of source strength.

Methylene chloride (dichloromethane) is a main ingredient in many common household products. One of these products is paint removers which are important because of an increase in home furniture refinishing. Methylene chloride is a very volatile substance which is metabolized upon inhalation to form COHb (carboxyhemoglobin). This can take place in levels which are toxic. Stewart and Harke [612] reported indoor methylene chloride levels with a maximum concentration of 1278 ppm.

3.3 AN OVERVIEW OF RESEARCH IN INDOOR AIR POLLUTION SOURCES

An overview of this subject suggests that much remains to be learned about the quantitative levels of indoor air pollution source strengths, both with respect to those pollutants which infiltrate (or are ventilated) into buildings and with respect to pollutants generated in the indoor environment. Studies of indoor-outdoor pollutant concentrations provide a surrogate for source strength measurements of ambient pollutants entering a building from outdoors, and there are many such studies for the common ambient pollutants, SO_2, CO, NO_x, photochemical oxidants, and TSP. The studies show that concentrations are typically (but not always) lower indoors than outdoors, with the indoor-outdoor ratio being lower for pollutants which react chemically with materials in the environment. This effect says something about pollutant behavior indoors, but little about the relative or absolute source strengths of ambient pollutants entering buildings. Ventilation studies (to be discussed in Section 9.0, Modeling of Indoor Air Pollution and in Appendix A) are required to estimate the quantities of ambient air pollutants introduced into buildings.

Indoor-generated pollutants arise from combustion in heating systems and stoves, from household cleaning and maintenance, from smoking, from hobbies, from the use of aerosol spray products, and from many other sources. There has been considerable research into the combustion product pollutants in the indoor environment, including measurements and calculations of actual source strengths. Estimates of pollutant emissions have been made for aerosol spray product propellants, and to some extent for the airborne pollutant products of smoking. Emission rates for the active ingredients of aerosol spray products have been difficult to estimate because the nature of the ingredients is often proprietary information not disclosed by manufacturers. Source strengths so far have been little investigated for emissions from diffuse sources such as cleaning, food preparation, pesticide application, painting and hobby activities.

Section 4.0

DISTRIBUTION AND BEHAVIOR OF INDOOR AIR POLLUTANTS

In Section 3.0 we discussed the sources of indoor air pollution, identifying the causes of pollutant occurrence in buildings. The focus of the discussion was upon points of origin (indoor-outdoor), source strengths, and the observed indoor concentrations of the pollutants.

Much of the early research into indoor air pollution was concerned with the relationships between outdoor pollutant levels and indoor pollutant levels, the tacit assumption being that outdoor sources of pollution were the important areas to consider. The research placed emphasis on "indoor-outdoor" concentration ratios. Studies of indoor-generated pollutants concentrated upon source strengths, and upon their contributions to the indoor-outdoor ratios.

A now growing body of research addresses another aspect of indoor air pollution, the dynamic behavior of the pollutant as it moves in the building from its point of origin to its ultimate fate. Research into the behavior of indoor air pollutants includes studies of their airborne transport, diffusion, chemical transformation, deposition and absorption. It is concerned with the spatial and temporal changes of pollutant concentration and character within the building, and with decay rates, residence times and the fate of pollutants.

The discussion which follows, based upon a review of the existing literature of indoor air pollution research, necessarily draws upon work already reviewed in Section 3.0, Sources of Indoor Air Pollutants. There is overlap in the literature and data reviewed because past researchers have not separated source and behavior characteristics of pollutants in their studies of indoor air pollution. An effort is made in what follows to make that distinction.

In ambient, outdoor conditions, air pollutants are transported and dispersed under the influences of wind speed, wind direction and the turbulence in the atmosphere. Pollutants in the ambient air are chemically transformed (if they are chemically reactive) through interaction with other airborne pollutants and through absorption and adsorption onto vegetation and other surfaces at ground levels; the rates at which some of these processes take place in ambient conditions are affected by temperature and humidity. The outdoor, ambient air pollution concentrations are thus a function not only of outdoor pollutant source strengths but also of air transport, diffusion, and chemical reactivity; all of which are influenced by ambient meteorology.

Indoor air pollution concentrations are also functions of pollutant source strengths (whether due to infiltration of polluted outdoor air or indoor generation of pollutants) and of air transport, diffusion and chemical reactivity occurring within buildings. The chemical reactivity and the internal air flow are both affected by temperature, and the reactivity may be affected by humidity as well.

In the outdoor environment the meteorological processes which affect air pollution concentrations occur on a large scale and cannot - in general - be controlled or altered significantly for air pollution control purposes by human efforts.

In the indoor environment the air movement and other elements of indoor climatology which affect indoor air pollution concentrations depend only in part upon outdoor conditions. They are also functions of building design, heating, ventilating and air conditioning system operation, and building use and occupancy. The mechanisms by which indoor air flows and indoor temperature and humidity (building climatology) are determined are discussed in detail in Sections 7.0 and 9.0 of this report, to which the reader is referred. They will not be discussed here. The distribution and behavior of pollutants indoors, as observed by various researchers and reported in the scientific literature, are discussed below. The discussions are categorized by types of pollutants.

4.1 SO_2 AND SULFATES

As discussed in Section 3.0, Sources of Indoor Pollutants, there are few indoor sources of sulfur dioxide, although in some cases SO_2 emissions have been attributed to faulty heating plants in buildings and dwellings fueled by oil or coal [69, 713]. Investigations of indoor SO_2 behavior have characteristically begun with consideration of an indoor-outdoor SO_2 concentration relationship. The residence time and fate of SO_2 in the indoor environment have typically been investigated in the context of these indoor-outdoor concentration studies.

To the extent that the concentration of SO_2 inside a building is a function of the ambient concentration of SO_2 outside the building it is also a function, in part, of the emission of SO_2 from outdoor sources in the upwind environs of the building. Outdoor source emissions of SO_2 are dependent largely on the sulfur contents of fuel used for power generation and heating and upon the quantities of fuel used. Outdoor emissions of SO_2 tend to be highest during the heating season in locations where the winters are colder, and highest in the cooling season in locations where the summers are warmer [39, 40].

Researchers have found indoor SO_2 levels to be generally (although not always) lower than outdoor concentrations [69, 397, 359, 694, 680, 42, 43, 433, 478, 243, 712, 670, 27, 65, 308].

Benson and his associates identified two factors as probable principal causes for the observed reduction of SO_2 concentration levels in the indoor environment [65]. First, SO_2 is a chemically reactive species and is adsorbed by walls and other interior surfaces; second, the frequently sharp and brief outdoor peak concentrations of SO_2 may be reduced by the lag time of transport into the building through narrow or small inlets and the relatively slower diffusion rates indoors where the turbulence characteristic of ambient outdoor air is lacking. Because of these factors the outdoor concentration peaks, frequently sharp and of short duration, are spread out and flattened when they reach the indoor environment [492].

Findings by Biersteker et al. [69] in Rotterdam homes and Yocom et al. [716] in a home in Hartford, Connecticut support a conclusion that the principal source of SO_2 in houses may be faulty heating system operations. Of two coal-fired houses sampled in the Hartford study, one was found to have significantly high indoor SO_2 concentrations. In this house the indoor SO_2 concentrations were completely dominated by this indoor source with peaks roughly coinciding with furnace stoking periods. The indoor concentrations over time were presented and shown to be much higher than those recorded outdoors [716].

In the Rotterdam study of indoor air pollution, only one home was found to have continuously higher SO_2 concentrations indoors than outdoors. In another, intermittently higher concentrations of SO_2 were found indoors than had been reported outdoors. The effect was believed to be due to faulty stoves or chimneys. This finding led the authors to say that "If 1 out of 100 houses has a failing chimney or a failing stove during smogs, one begins to wonder how far indoor concentrations of air pollutants play a role in causing premature death in persons with failing circulation and respiration and what role CO plays in the process" [69].

In a laboratory room at the Department of Chemical Engineering and Chemical Technology, Imperial College, London, England, Wilson [674] measured the decay rates of sulfur dioxide concentrations which followed the closing of windows which had been open to the polluted London atmosphere. Simultaneous concentration measurements of the decay of known amounts of nonreactive helium and of SO_2 (introduced at the start of the experiment) permitted estimates of the extent to which SO_2 was absorbed onto surfaces or otherwise removed by indoor sinks. "The rate of air change in the room was measured by liberating some helium at the start of an experiment and determining the concentration at intervals with a chromatograph." The helium was not adsorbed and the reduction of its concentration was a measure of gas leakage rates out of the closed room which would affect SO_2 and helium alike.

Wilson found that SO_2 had a half-life of 40 to 60 minutes and that the equilibrium concentrations of SO_2 in the test room were controlled mainly by processes at the surface rather than by transport processes. Wilson's work is noteworthy, in addition, for his experiments with a controlled concentration of SO_2 liberated within the test room at a constant rate. Air containing a 2 mg/m^3 concentration of SO_2 was placed in contact with absorbing surfaces in a closed vessel over measured periods of time, after which SO_2 concentrations were again measured. The resulting reductions of SO_2 concentration were a measure of absorption. Table 13 illustrates this. The authors said "that the walls, floor and treated wood surfaces had little effect in removing sulfur dioxide; and that only the ceiling was reasonably effective" [694].

TABLE 13. CONCENTRATIONS OF SO_2 ABSORBED BY VARIOUS MATERIALS [694]

Material	Sulfur Dioxide Absorbed (mg/m^2)	
	After 1/2 Hour	After 1 Hour
Varnished Wood	0,11	0,11
Painted Wall	0,13	0,13
Floor	0,36	0,36
Ceiling	0,51	0,99
Softwood	1,70	2,82
Corduroy	0,65	1,20
Knitted Wool	1,85	3,46

Wilson concluded that an increase in transport to surfaces which have reached a state of equilibrium in SO_2 adsorption capacity cannot reduce the airborne SO_2 concentrations further. This finding, that materials reach a capacity for SO_2 adsorption, was also observed by Biersteker et al. [69] and Grafe [243]. In these investigations, increased outdoor SO_2 concentrations and subsequent increased inflow of SO_2 were observed to be ineffective in changing the indoor adsorption patterns.

A series of papers [589, 591, 590, 588, 592, 587, 250] on adsorption by indoor surfaces shows, that of the surfaces studied, leather is the most efficient surface for sulfur dioxide adsorption followed by natural fibers (wool, cotton). In general organic materials such as leather and natural fibers are more efficient adsorbers of SO_2 than inorganic materials or manufactured organic materials such as artificial fibers. Spedding [589] concludes that adsorption of SO_2 by many surfaces is dependent upon the moisture content of the surfaces and thus of the atmosphere. Previous studies have reached the same general conclusions [587, 681, 315].

Cox and Penkett [144] found that the first order decay of SO_2 indicates an irreversible adsorption on the surface of the material. As humidity is raised from 30 to 86 percent, the speed at which SO_2 is deposited upon gloss paint is increased by a factor of 12.7 [144]. The authors hypothesize that the SO_2 is probably taken up by a film of water associated with the surface; after adsorption it will be converted to sulfate at a rate dependent upon the extent to which materials from the surface are dissolved in the water film. They concluded that "Sulfur dioxide is going to disappear very rapidly onto the walls of any containing system at high relative humidities" [144].

Benson et al. [65] conclude that sulfur dioxide is removed from interior air by adsorption at a rate dependent primarily on the properties of the interior surfaces and only slightly on the rate of transport to the surfaces. The authors reported Wilson's [694] findings that "stirring" the air was effective in reducing SO_2 concentrations by 10 to 40 percent; the higher the initial concentration in the room the greater was the percentage reduction. The reviewers do not discuss the role higher relative humidity plays in increasing SO_2 adsorption on all interior surfaces.

There have not been studies which directly addressed the behavior of sulfuric acid and other sulfates in the indoor environment. It has been determined from previous investigations of atmospheric chemistry processes that SO_2 does not remain unaltered in the atmosphere, but is oxidized to sulfuric acid and other sulfates by several environmental-dependent mechanisms (most of which are not well understood) involving reactive agents such as photochemical smog, ammonia, catalytic metals, and fine particulates [664]. The rate of formation and, to some extent, the final sulfate form, are determined by the different mechanism paths. The most important sulfate mechanisms identified to date are categorized in Table 14 on the following page, reproduced from work by Wilson and his associates [695]. Those sulfate compounds currently known to be formed in the atmosphere from gas-particle conversions involving SO_2 oxidation are listed in Table 15 from Wilson [695], which in addition shows those sulfates emitted directly by industrial or by natural sources.

Studies of the $SO_2 \rightarrow$ sulfate transformations are proceeding vigorously in the larger context of ambient air pollution research. For example, the Electric Power Research Institute Inc. (EPRI) is sponsoring the on-going Sulfate Regional Experiment (SURE). Currently, efforts in this research are directed towards an experimental design for a major regional air chemistry study of how particulate sulfate concentrations may relate to sulfur oxide emissions based upon an evaluation of existing air quality data, chemical processes, and numerical modeling capabilities.

Of the transformation mechanisms known, few, if any, give promise of providing an explanation for the conversion of SO_2 to sulfate in an airborne phase in an indoor residential environment. A principal reason for this is the relatively long reaction time for $SO_2 \rightarrow SO_4$ reactions (typically greater than the air exchange rates of residences) and the short times of SO_2 in the indoor environment (typically less than an hour).

4.2 CARBON MONOXIDE

Benson et al. [65] concluded that carbon monoxide indoor-outdoor concentration relationships are similar to those of sulfur

TABLE 14. MECHANISMS BY WHICH SULFUR DIOXIDE IS CONVERTED TO SULFATES [illegible]

Mechanism	Overall reaction	Factors on which sulfate formation primarily depends
1. Direct photooxidation.	$SO_2 \xrightarrow[\text{water}]{\text{light, oxygen}} H_2SO_4$	Sulfur dioxide concentration, sunlight intensity.
2. Indirect photooxidation.	$SO_2 \xrightarrow[\text{organic, oxidants, hydroxyl radical (OH)}]{\text{smog, water, } NO_x} H_2SO_4$	Sulfur dioxide concentration, organic oxidant concentration, OH, NO_x.
3. Air oxidation in liquid droplets.	$SO_2 \xrightarrow{\text{liquid water}} H_2SO_3$ $NH_3 + H_2SO_3 \xrightarrow{\text{Oxygen}} NH_4^+ + SO_4^=$	Ammonia concentration.
4. Catalyzed oxidation in liquid droplets.	$SO_2 \xrightarrow[\text{heavy metal ions}]{\text{oxygen, liquid water}} SO_4^=$	Concentration of heavy metal (Fe, V, Mn) ions.
5. Catalyzed oxidation on dry surfaces.	$SO_2 \xrightarrow[\text{carbon, particulate}]{\text{oxygen, water}} H_2SO_4$	Carbon-particle concentration (surface area).

TABLE 11. KNOWN ATMOSPHERIC SULFATES [illegible]

Formula	Names	Sources	Notable chemical properties	Probable Size class by mass particle Diameter, Dp
H_2SO_4	Sulfuric acid (oil of vitriol)	Atmospheric oxidation of SO_2; direct from manufacturing.	Strong acid, very hygroscopic (drying agent at low RH).	0.1 - 1.0 µm
NH_4HSO_4	Acid ammonium sulfate	Oxidation of SO_2 with NH_3 addition.	Strong acid, hygroscopic.	0.1 - 1.0 µm
$(NH_4)_3H(SO_4)_2$	Triammonium acid disulfate (Letovicite)	Oxidation of SO_2 plus NH_3.	Acidic, deliquescent (?) at ~69% RH.	0.1 - 1.0 µm
$(NH_4)_2SO_4$	Ammonium sulfate (Mascagnite)	Oxidation of SO_2 plus NH_3.	Weak acid, water-soluble, deliquescent at 80% RH.	0.1 - 1.0 µm
Na_2SO_4	Sodium sulfate (Glauber's salt)	Paper pulping by kraft process.	Water-soluble, deliquescent at 84% RH; relatively inert.	D_p > 0.5 µm (uncontrolled pulp mill)
$CaSO_4$	Calcium sulfate (gypsum)	(1) Wind-blown dust. (2) Manufacture of gypsum products.	Low solubility in H_2O; relatively inert	D_p > 1µm
$MgSO_4$	Magnesium sulfate (Epsom salts)	(1) Sea spray. (2) Paper pulping.	Very hygroscopic; relatively inert and non-toxic.	D_p > 1 µm (sea spray) D_p > 0.5 µm

dioxide in that (a) concentrations are generally higher outdoors than indoors and (b) increases in concentrations outdoors do not lead to proportional increases inside. Further, they point out that short-term peaks in outdoor CO concentrations, like those of SO_2, are not reflected by indoor concentration patterns. There are important differences, however, in the reactivity of the two gases and in their residence times within buildings. Carbon monoxide is relatively unreactive and decays very slowly compared to SO_2. Further, CO is of particular interest because it is not only an outdoor-generated pollutant but is an indoor-generated product, arising from gas-fired appliances, leaky furnaces and chimneys, and attached garages. The significance of indoor-generated CO is substantially greater than that of indoor-generated SO_2.

In a comprehensive study conducted by the General Electric Company [233] the behavior of carbon monoxide was investigated in two high rise buildings, one of them an air-rights structure. As reported in the section on pollutant sources, indoor CO concentrations were normally lower than outdoor concentrations at all heights above the roadway when outdoor concentrations are high. Conversely, indoor concentrations were higher than outdoor concentrations when outdoor concentrations were low. At heights greater than 100 feet above the roadway, concentrations of CO were larger indoors than outdoors; this was attributed to the entrapment of CO within the building (i.e., inside the building it was not removed by the air transport processes which were operating actively at this level to dissipate CO in the air outside the building) [233].

In the comprehensive study of buildings in Hartford, Connecticut by Yocom [713], carbon monoxide was monitored at four locations; far outdoors, near outdoors, near indoors and far indoors. Far indoor/far outdoor concentration ratios were found to approximate 1.0 for all structures when a long averaging time was used as a basis for comparison. For comparisons of short-term CO concentrations, however, concentrations indoors were found to lag behind those found outdoors. Outdoor CO concentrations showed gradual peaks corresponding to the hours from 6 to 9 A.M. during which outdoor CO concentrations steadily rose above those found indoors. However, as the CO concentrations were subsequently depleted outdoors, indoor concentrations rose above those found outdoors but to levels less than those found earlier outdoors. The authors also determined an exponential decay constant for carbon monoxide by both closing off the ventilation and "spiking" the indoor atmosphere with CO.

The authors described the response indoors to peak outdoor concentrations at one of the homes monitored with the windows and doors closed and the air conditioner turned off as sluggish, but highly dependent upon the air exchange rate of the building monitored. Further, the authors found that the heating system had little effect on CO levels except in a home in which a coal-fired hot air heating system was believed to be faulty. Here the CO and SO_2 levels were found in concentrations high enough to be of concern for possible adverse health effects. Finally, the authors found that the carbon monoxide emissions from a gas stove had a significant effect on indoor CO levels [713].

In a study conducted in California on the relation between indoor and outdoor concentrations of nitrogen oxides, carbon monoxide was also monitored both inside and outside a building [150]. The investigators reported results similar to those found by Yocom et al. [713] in which the CO concentrations indoors lagged behind the peak concentrations outdoors; these latter corresponding to peak automobile traffic nearby. The authors concluded, after finding that nitrogen oxide showed similar temporal behavior, that both NO_x and CO levels could be reduced by restricting the intake of outside air during these periods.

Studies of the concentrations and behavior of carbon monoxide emitted from gas-fired appliances in the indoor environment have shown that this source can contribute concentrations of significant amounts [143]. The Institute of Gas Technology in conjunction with Battelle Columbus conducted a survey of 67 homes equipped with gas cooking kitchens in order to determine the concentrations of CO and NO_x levels in the kitchen. The investigators monitored air 6-10 feet from the cooking unit at a height of about 3-1/2 feet from the floor. Samples of air were collected over a period of one hour from the start of cooking the main meal. The authors concluded that the concentrations of CO were negligibly small compared with the 1-hour standard of 35 ppm. In 71 percent of these homes, the concentrations were less than the 8-hour standard of 9 ppm. One of the homes, however, had a CO concentration for one hour above the 35 ppm level (39.4 ppm) as a result of a badly adjusted oven. A repeat sample after adjusting the oven measured

7.1 ppm during cooking of the same meal [184]. The finding concerning a badly adjusted oven represented 1.75 percent of the homes surveyed. While not statistically significant in itself, the finding would be of concern if this percentage of maladjustment were an adequate representation of all homes equipped with gas-fired appliances, particularly considering the fact that the 39.4 ppm CO concentration was monitored as far away as 6 to 10 feet from the cooking unit.

In a more recent study conducted in Hartford, Connecticut, CO concentrations were monitored in the kitchen and three other locations in four private residences for two-week periods in the spring and early summer of 1973 and again in the following fall and winter [143]. The investigators found that the CO concentrations were higher inside than outside, with one exception, and always higher in the kitchen than in other parts of the house. Further, the authors found 40 percent of the indoor concentrations above the 8-hour NAAQS for CO at all three indoor locations in House No. 4 where CO concentrations were highest among the four houses surveyed. Table 16 shows results of this survey.

It can be seen from this table that the CO concentrations were differentially dependent upon background or outside concentrations and indoor stove use. In addition, the patterns of indoor CO are influenced by interior design features and ventilation characteristics. Further, the half-life of CO was found to be 2.1 hours in House No. 2 during an unoccupied period [143].

Most recently the Lawrence Berkeley Laboratories conducted pilot measurements of combustion-generated indoor air pollution for the

TABLE 16. SUMMARY OF INDOOR/OUTDOOR CO DATA IN EACH HOME FOR BOTH SEASONS

House Number	Sampling Period	Daily Average CO Concentration of Each Location $\mu g/m^3$					Total Stove (Oven Plus Burners) Use Min./Day	Number of Days of Valid Data
		Kitchen Over Stove	Kitchen 1 m from Stove	Living Room	Bed Room	Outside		
1	Spring - Summer	-	4490	4070	4170	5480	198	9
	Fall - Winter 1st Half	4190	5520	5250	-	1670	108	4
	Fall - Winter 2nd Half	4790	4210	-	3850	2510	(Unavailable)	6
2	Spring - Summer	3000	-	3080	2900	2960	43	3
3	Spring - Summer	4510	-	3210	2680	2250	37	15
	Fall - Winter 1st Half	7820	6420	5070	-	3380	68	6
	Fall - Winter 2nd Half	7130	6620	-	5500	2500	115	8
4	Fall - Winter	9070	9000	8190	-	2410	201	6

Adapted from Cote et al. [148].

U.S. Energy Research and Development Administration at six homes in Berkeley and Albany, California; all fitted with gas heating systems and five with gas-fired stoves. Results of the CO measurements shown in Tables 8 and 9 in Section 3.0, again are observed to exceed the 1-hour NAAQS for CO [308].

Radford [504] reported that of 302 old houses surveyed in East Baltimore 20 percent had elevated levels of 10 ppm or more of CO, 4 percent showed levels at 20 ppm or more and 1 percent exceeded 50 ppm. In the houses where the higher CO concentrations were found, the problem was traced to unvented space heaters or stoves used for heating, to oil or gas fired furnaces used for central heating and to combinations of these sources. These data may be compared with an analysis conducted by Morrison [436] of deaths in 1967 due to accidentally induced CO poisonings. Although 68 percent of the death certificates revealed automobiles as the leading cause of CO poisonings, heating equipment accounted for 26 percent (over 300) of these deaths. Of these related to heating equipment, 11 percent were due to furnaces, 19 percent specifically identified as space heaters and 64 percent were caused by other sources including stoves, refrigerators and charcoal.

Carbon monoxide, as a product of the combustion of tobacco, has been studied as a pollutant to which the smoker and nonsmoker are exposed. The smoker is exposed through direct inhalation of the smoke (mainstream) while the nonsmoker involuntarily inhales the tobacco smoke from the environment (sidestream). The exposures to carbon monoxide by the "involuntary smoker" from mainstream and sidestream smoke have been the subject of increasing study in recent years. Although carbon monoxide is often used as an indicator of other pollutants resulting from tobacco, because it is both easy to measure and predict, it has been studied in its own right as being a possible health risk to nonsmokers [656]. Bridge and Corn have noted that "the CO generated by one cigar is approximately 1.7 to 2.5 times as much as that generated from simultaneously smoking three cigarettes" [88].

Carboxyhemoglobin (COHb) level measurements for groups of passive smokers have been conducted by various investigators in attempts to assess the exposure and health risk of CO from smoking [39, 40, 41, 270, 531, 610].

In a study conducted to assess the nonsmokers' exposure to smoke, Bridge and Corn [88] monitored carbon monoxide in two rooms before and after two 90-minute parties where roughly half of the participants were smokers. In the two rooms (5120 and 3570 ft^3) background concentrations of CO were 1 and 2 ppm CO respectively. During the parties the average CO concentrations were 7 and 9 ppm respectively attributed to 50 cigarettes and 17 cigars at the first party and 63 cigarettes and 10 cigars at the second party. Bridge and Corn found that "if the CO emitted by room occupants is taken into account, the measured concentrations are reduced to about 6.5 and 8 ppm for the first and second parties, respectively" [88]. Results of their work are shown in Table 17.

Bridge and Corn concluded that "concentrations of CO from cigarette and cigar smoking do not present an inhalation hazard to nonsmokers. However, suspended particulate matter generated from cigarette and cigar smoking was calculated to reach concentrations considered to be excessive using the criterion of ambient air quality standards for suspended particulate matter suggested by Federal criteria ($75\ \mu g/m^3$)" [88].

TABLE 17. MEASURED CONCENTRATIONS OF CARBON MONOXIDE IN THE EXPOSURE CHAMBER FROM TOTAL CIGAR SMOKE FOR ONE CIGAR SMOKED AT EACH OF 1, 3, 6, and 8 VOLUMETRIC AIR CHANGES/HOUR [88]

Exposure Chamber Exhaust Rate (cfm)	Air Changes Per Hour	No. of Cigars Smoked	Smoking Time (Minutes)	Butt Length (mm)	CO Conc (ppm)*	
					Peak	Initial
5.4	1	1	28	51	57	5
5.4 (repeat)	1	1	28	50	58	1
45.4	8	1	30	28	24	2
45.4 (repeat)	8	1	28	35	25	1

* Ambient Air Quality Standard for 1 Hour is 35 ppm and for 8 Hours is 9 ppm.

In a study to assess the health aspects of smoking in transport aircraft carbon monoxide concentrations were monitored at four locations in 18 Military Aircraft Command jet aircraft for 6 to 7 hour flights and in eight civil domestic flights of 45 minute to 1 hour durations. For the MAC flights the highest CO concentration was 5 ppm CO in one location in one flight. In the total of 72 MAC flight samples, 32 were 2 ppm or less, 25 were 3 ppm, 14 were 4 ppm and 1 was 5 ppm. For the domestic flights, no CO concentrations greater than 2 ppm were observed out of 24 samples taken. This discrepancy in MAC and civil aircraft flights is attributed to the more rapid exchange of air in civil aircraft and the almost CO-free air entering the aircraft at cruising altitude [662].

In a study conducted by Penkala and de Oliveira [486] a literature review was conducted to offer a comparison to the authors' subsequent measures of CO and Suspended Particulate Matter (SPM) in an exposure chamber. The authors' results are presented with those of other authors in Table 18. The results of the authors' measurements of CO in a room occupied by a smoker and a nonsmoker are shown in Table 19.

In comparing the removal rates of CO and SPM in the exposure chamber the authors found the concentration half-lives to be 83.5 and 4.8 minutes respectively. Penkala and de Oliveira concluded that CO should not be used as a tracer for tobacco smoke without correcting for this difference [486].

Public gatherings for sporting events, concerts and other activities are also sources for the accumulation of concentrations of tobacco smoke. Elliot and Rowe [185] measured Total Suspended Particulate (TSP), CO and benzo(a)pyrene before and after events at three arenas. In one event attended by 2,000 persons the arena was not air conditioned and had no signs restricting smoking. The background carbon monoxide was 3.0 ppm which rose to 25 ppm during the event.

Another place of public assembly in which CO may be found in high concentrations is an ice skating rink. Rinks are peculiar sources of CO not only from tobacco smoke but also from the large propane-fueled ice resurfacing machines. In one rink in Seattle monitoring

TABLE 18. MEASURES OF CO AND SPM IN AN EXPOSURE CHAMBER [485]

Investigator	Milligrams Mainstream Smoke	CO per Cigarette Sidestream Smoke	Total	Ratio Sidestream Mainstream CO
Rosanno and Owens (1976)	23	63	86	2,75
Bridge and Corn (1972)	22	--	124	9,4
Bogardus and Ramsdell (1968)	--	--	55	--
Westcombe and Robeald (1967)	22,0-28,8	--	82-155	2,75-4,4
Harke (1972)	--	--	77	--
Penkala and De Oliveira (1975)	--	--	82,7	--

TABLE 19. ESTIMATE OF CO CONCENTRATIONS IN A 7,2 m^3 ROOM OCCUPIED BY A SMOKER AND A NON-SMOKER [455]

Ventilation Rate (air changes/hour)	CO Concentrations (mg/m^3)		
	Minimum	Maximum	Mean
0	15,2	22,5	18,8
1	3,3	10,8	6,2
2,1 good ventilation practice	1,1	8,4	3,8
7,5 good ventilation practice	0,0	7,3	1,2

took place after 15 children became ill and suffered a variety of symptoms including headaches, nausea and vomiting. Carbon monoxide concentrations averaged for one hour were found to be as high as 304 ppm. Table 20 shows the average CO concentrations at this rink and Table 21 shows the results of a survey of other rinks conducted to determine if they too were a significant source of CO exposure [336].

In the ice skating arena a gas-powered resurfacing machine was used. CO levels rose to a level of 175 ppm in 17 minutes, and remained at 170 ppm 15 minutes after the machine was stopped. The authors estimate that there are approximately 600-700 ice skating arenas in the United States, most of which use ice resurfacing machines that produce significant amounts of CO. Although catalytic mufflers and better ventilation practices are offered as solutions, the authors suggest electrically powered ice resurfacing machines are probably best [336].

Although "indoor" is usually taken to mean the interior of a building, it can also define the passenger compartments of vehicles. Of significant concern to the public is the exposure to CO concentrations while riding in or operating motor vehicles since automobiles are by far the largest anthropogenic source of carbon monoxide. In urban areas such as Boston, Washington, D.C. and Los Angeles more than 98 percent of the CO emissions are produced by automobiles. While many researchers have studied emissions of CO from automobiles and exposures to ambient concentrations of CO in urban areas, there have been few studies of the

TABLE 20. CONCENTRATIONS OF CO RECORDED IN ICE-SKATING ARENA DURING OPERATION OF PROPANE-POWERED ICE-RESURFACING MACHINE GENERATED FOR 10 MINUTES EVERY 1 OR 2 HOURS [356]

Clock (Hours)	CO Level (1 Hour Average) ppm
4-5	214
5-6	304
6-7	234
7-8	225
8-9	186
9-10	157
10-11	261
11-12	319
EPA 1-hour standard	35

TABLE 21. RESULTS OF INITIAL SURVEY OF CARBON MONOXIDE LEVELS IN ICE SKATING ARENA IN KING COUNTY, WASHINGTON [356]

Ice Skating Arena	CO Level (Maximum) (ppm)	Number of Inspections	Remarks
Highland	250	4	Arena now opens doors to augment ventilation
Ballard	45	1	Doors opened prior to test (not normally done)
Bellevue	75	1	Machine run only 7 minutes (normally machine runs 10-15 minutes)
Burien	100	1	
Crossroads	175	1	
Coliseum	12	1	No public skating

CO exposures to commuters in the enclosed environments of automobiles, mass transit and buses.

Cortese and Spangler [142] conducted a study of CO exposures to commuters utilizing private automobiles and mass transit by equipping 62 volunteers with personal monitoring instruments for measurement of the CO concentrations to which they were exposed. The results of the aggregate personal exposure data revealed that for all commuting concentrations, 10 percent of the values are greater than 21 ppm, 5 percent are greater than 26 ppm and 1 percent are greater than 36 ppm. In analyzing concentrations reported at fixed locations the authors concluded that these ambient CO concentrations measured at these fixed sites significantly under-represent the 1-hour exposures actually experienced by commuters. The investigators demonstrated that the method of travel and exposure to cigarette smoke were the two factors significantly influencing personal exposures to CO during commuting. Travel on rail mass transit resulted in a CO exposure of less than half that of auto travel.

Peterson and Sabersky [489] performed a series of experiments to determine the concentrations of certain pollutants inside a car under typical driving conditions. The experiments were conducted during the summer months in the Los Angeles area and measurements were taken of CO, O_3, NO and NO_x. All of the experiments were conducted with the vehicle windows closed and with the air conditioner on during most of the vehicle run. Samples were taken within the vehicle interior and from outside air drawn into an analyzer through a duct passing out through a slit in the door window. The authors concluded that inside CO concentrations on the average were the same as those in the surrounding atmosphere outside and were below the National Ambient Air Quality Standard levels for CO. Although the magnitude of the concentrations were 15 to 25 ppm, the concentrations were sometimes higher for short periods of time. In one severe traffic congestion the concentration reached 45 ppm for 3 minutes.

It is noteworthy, however, that the ambient air concentrations monitored at fixed locations near the route showed a peak reading of 8 ppm CO. The number of values exceeding the 8-hour NAAQS for CO in Burbank was 1,101 of a possible 4,406 valid values in 1973. Further, since attempts were made to monitor under a range of typical driving conditions in Los Angeles, the time period on the freeway sections which were often congested was minimal; much of the monitoring was conducted during off-peak conditions. Presumably, the CO exposures to commuters in Los Angeles during peak traffic conditions are often significantly above NAAQS levels, particularly on days when the one-hour and eight-hour standards are exceeded at fixed locations.

Brice and Roester [84] monitored concentrations of CO in moving vehicles in six cities. The data collected showed a maximum concentration of CO inside moving vehicles, in traffic, of 77 ppm (St. Louis). In another report exposures to levels of CO on school buses were found to be higher than the recommended one-hour standard of 35 ppm [356]. This latter study was performed after several children became ill, two requiring hospitalization.

4.3 CARBON DIOXIDE

Like carbon monoxide, carbon dioxide is a relatively stable pollutant and would be expected to have a relatively long residence time in indoor air. Unlike carbon monoxide, however, carbon dioxide concentrations indoors would likely be a function of the number of occupants. Additionally carbon dioxide is a product of complete combustion and is therefore emitted by gas stoves and appliances and building heating plants. Only one reference was found concerning the indoor concentrations of carbon dioxide. Ishido [326] found indoor levels of CO_2 ranging from 0.03 to 0.32 percent (300 to 3,200 ppm). This is from 1 to 10 times the normal ambient air level of CO_2 [557]. Bush and Segall reported that CO_2 is not removed from the indoor environment by air conditioning [100].

4.4 NITROGEN OXIDES AND NITRATES

Concentrations of nitrogen oxides found indoors are attributed to both infiltration from the outdoor environment and to generation from household heating and cooking appliances, primarily gas-fired. In field measurements in a home in Hartford, Connecticut, Cote et al. [143] found that the half-life of NO was 1.6 hours while NO_2 decayed with a half-life of 0.6 hours. Further the investigators found that the ratios of NO_2 to NO varied somewhat but that there was generally more NO than NO_2 generated from the gas stove. Hollowell et al. [308] reported concentrations of NO which were more than twice those of NO_2 in a home with a gas-fired stove with no duct and an exhaust fan off. Table 22 shows the results of their findings.

TABLE 22. CONCENTRATIONS OF NO AND NO_2 ($\mu g/m^3$) OBSERVED IN HOMES WITH GAS OVENS* [308]

Home ID #	2		3	4
Ventilation Conditions	No Duct Fan Off	No Duct Fan On	Duct No Fan	Duct No Fan
NO ($\mu g/m^3$)	2000	1000	500	150
NO_2 ($\mu g/m^3$)	850	320	150	95

* Measurements in center of kitchen, approximately 1.5 meters above the floor, with the gas oven at 550°F for approximately 20 minutes.

The investigators found "elevated indoor particulate nitrogen levels" (this is Hollowell's terminology) in the home equipped with a gas furnace [308]. These results compare favorably with those reported by Eaton et al. [178] where a maximum NO_x value of 1.0 ppm (2000 ug/m^3) was observed in a kitchen after a 6-minute cooking time with a gas burner. In controlled tests for indoor oxides of nitrogen the investigators also reported higher concentrations of NO than NO_2. Derham et al. [158] reported on the concentrations of nitrogen oxides inside and outside a building in Pasadena, California, a city where ambient concentrations of these pollutants are known to be high. NO was found to behave very similarly to monitored CO with peaks associated with rush hour automobile traffic outdoors; since their behavior was similar no significant chemical reactions were believed to be involved in establishing the indoor concentrations of NO. Indoor O_3 concentrations during the experiments were relatively low when NO was present. High NO and NO_2 concentrations were found in the months from about October to March whereas high O_3 concentrations were found in the months from March to October. Finally, the results support findings that NO and O_3 do not co-exist indoors except in small quantities [158].

No investigations have been made to determine possible indoor mechanisms for nitrate or nitrosamine formation although Hollowell et al. [308] made some preliminary tests in a home equipped with a gas furnace. Experiments to measure those nitrogen species in kitchens equipped with gas-fired appliances would help to establish these mechanisms if such conversions take place.

Indoor NO and NO_2 concentrations, to the extent that these arise from outdoor-generated pollution, are dependent upon the location of the building in relation to the point and area sources at which NO and NO_2 emissions are generated. Atuomobiles are the major source of NO and NO_2 emissions. The location of the building in relation to automobile traffic patterns will, therefore, have an important influence on the levels of outdoor concentrations of NO_x which are available to enter the building.

Presumably, the NO/NO_2 ratio would be higher in buildings close to roads than those further away. In the latter case the NO/NO_2 ratio will not only be lower but might as a result be subject to relatively higher concentrations of O_3 (which is not generated directly by automobile traffic but indirectly through photochemical reactions involving automotive emissions which have typically moved many miles from the emission sources by the time oxidant generation occurs). A further discussion of reasons for the relatively low O_3 concentrations near heavily travelled highways appears later, in Section 4.5. These conditions, as taking place outdoors and monitored at continuous monitoring stations in urban and suburban locations, have been discussed by Altschuller and Bufalini in 1971 [8].

Observed concentrations of NO are highly dependent upon the meteorological conditions: indoor concentration measurements taken on a day on which there was no inversion layer indicated low NO levels at all times [158]. Figure 4 from the Derham et al. study, shows the correlation between external and internal NO levels.

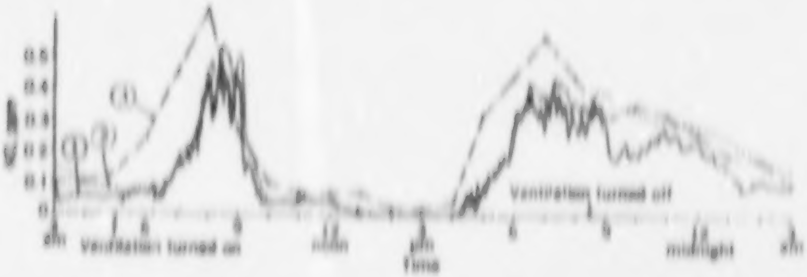

Figure 4. Relative NO levels as recorded outdoors (1), indoors (2), and as reported by the Pasadena APCD station (3) on a typical day [158].

4.5 PHOTOCHEMICAL OXIDANTS

Ozone and PAN (peroxyacetyl nitrate) are secondary pollutants in the ambient atmosphere, typically arising from interactions of automobile-generated hydrocarbons and NO_x emissions in the presence of sunlight. Ozone may also be generated independently in indoor and outdoor environments through electrical discharge at equipment such as air cleaning precipitators and fluorescent lights.

Ozone and PAN are also highly reactive species and, like SO_2, do not persist in high concentrations indoors even when outdoor concentrations are high, because of rapid decay through adsorption on indoor surfaces. O_3 and PAN concentrations indoors are highly dependent on the location of the building monitored in relation to large urban areas. Ambient concentrations of O_3 and PAN are a function of particular meteorological conditions of low wind, low atmospheric stability and large amounts of sunlight as well as the presence of sources of hydrocarbons and NO_x. The topography of the urban area, its size, and its location govern the climatological history of episodic pollution potential [309]. The daily generation of NO, NO_2 and hydrocarbons, particularly from automobile emissions, during these episodic conditions determine the concentrations of O_3 and PAN within the large urban plume. The location of the building monitored, in relation to wind direction and the urban plume, largely determines the concentrations of outside O_3 and PAN which can infiltrate into the indoor environment. The immediate vicinity of a building near a heavily traveled highway (including buildings within the urban core) may have concentrations of O_3 which are relatively low. This observation has been attributed to the ability which high concentrations of NO, emitted from automobiles, have to scavenge the O_3. Investigations of O_3 and NO indoors have verified this relationship [561]. Ambient O_3 concentrations are high in the warmer months and occur during daylight hours. Figures 5, 6, and 7 show the indoor-outdoor concentrations of O_3 on three summer days in California [534, 439].

Ozone does not usually originate in significant quantities in indoor environments, its levels being closely related to the outdoor ozone levels. Indoor-generated ozone, from electrical equipment operations, is not believed to be an important source in the nonworkplace indoor environment. Many of the studies concerned with the behavior and fate of ozone indoors have involved numerical models which relate indoor ozone concentrations to those outdoors. An example of this is the Hales et al. [262] linear combination model, which when used for verification purposes, was found to be in agreement with actual ozone concentrations in hallways of the selected test area. The concentrations were found to vary from room to room depending on parameters such as local ventilation and room geometry. The Hales et al. [262] study served to verify the theoretical ventilation model of Shair and Heitner [561]. Development of this model was based, in part, on results of earlier tracer experiments to obtain quantitative data regarding actual residance time distributions of the tracer (SF_6) in rooms and hallways [171]. A simple "stirred tank" ventilation model was used to interpret experiments involving the decay of ozone in the presence of various common materials

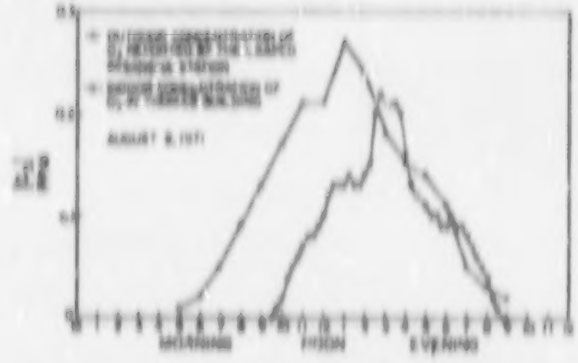

Figure 5. Ozone concentration vs. time of day for Thomas Building, August 5, 1971.

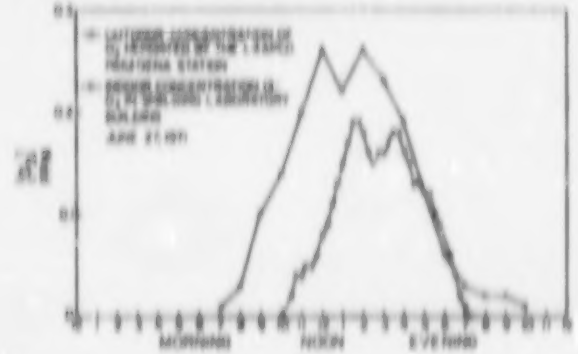

Figure 6. Ozone concentration vs. time of day for Spalding Laboratory, June 27, 1971.

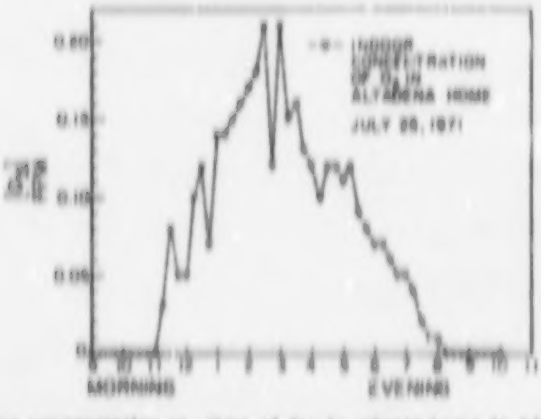

Figure 7. Ozone concentration vs. time of day in private home in Altadena, July 25, 1971.

Note: All figures are from Sabersky et al. [556]

in a lucite chamber [534]. All these modeling attempts utilize the fact that ozone typically undergoes a first order heterogeneous decomposition mechanism. Studies conducted in rooms of various sizes, indicated the ozone decay rate is directly related to the surface-to-volume ratio [439]. Table 23, from the same study, shows the measured values of ozone decomposition rates for several common surfaces, as determined in the lucite chamber. It can be seen that the higher rate constants are characteristic of materials such as rubber, fabrics and plastics; metal and glass have lower rate constants. Hales et al. [262] observed that rooms with rugs, excess furniture, excess books and papers had lower ozone levels than did those with concrete floors or those rooms which appear to be neater, with few books and papers present.

In research by Mueller et al. [439], ozone decomposition studies were performed in a closed bedroom. The results showed a short, six minute half-life of ozone in the bedroom which suggests rapid decomposition of this pollutant after it penetrates a typical living space. Research by Ellis and Tometz [187] tested the "ozone decomposing catalytic efficiency" (the author's terminology) of various materials at room temperature in a laboratory. The results of their efforts are shown in Table 24; the best catalysts are coconut charcoal and activated carbon. Most researchers who have studied ozone behavior indoors have concluded that additional studies should be conducted to further understand the detailed mechanisms of ozone decay on common surfaces.

TABLE 23. MEASURED VALUES OF OZONE DECOMPOSITION RATES FOR SEVERAL COMMON SURFACES [334]

Material	K, $ft^3/ft^2 \cdot min$
Cotton muslin	0.314 → 0.029
Lamb's wool	0.208 → 0.016
Neoprene	0.19 → 0.03
Plywood (1 side varnished)	0.06 → 0.01
Nylon	0.061 → 0.001
Polyethylene sheet	0.046 → 0.020
Linen	0.0183 → 0.0107
Lucite	0.012 → 0.001
Aluminum	0.002 → 0.001
Plate glass	0.002 → 0.001

TABLE 24. RESULTS OF TESTS OF OZONE-DECOMPOSITION CATALYTIC EFFICIENCY OF VARIOUS MATERIALS [187]

% Ozone Removed	Materials
90 - 100	coconut charcoal, activated carbon
70 - 80	NiO, NiO-CuO mixture, NiO-Fe_3O_4 mixture, Hopcalite
50 - 60	Ni_2O_3, MnO_2, Ag, Fe_3O_4, SnO, Pb_3O_4, Ag_2O, NiO-SnO mixture
40 - 50	SnO-Fe_3O_4 mixture, CuO-Fe_3O_4 mixture, CoO, Fe_2O_3, CuO, Sb_2O_5, PbO
30 - 40	ZnO, Al_2O_3, Cr_2O_3, CuO-SnO mixture
10 - 20	MgO, 500 W lamp, Ni
0 - 10	CrO_3, CdO, Bi_2O_3, glass wool, zeolite catalyst, silica-alumina catalyst, F

4.6 HYDROCARBONS (NONPHOTOCHEMICAL ORGANICS)

A study by Bridbord and others in 1975 [86] examined the behavior of halogenated hydrocarbons in indoor environments. The authors described a theoretical basis for calculating the rate of decay of indoor pollutant concentrations (assuming a chemically inert pollutant) as a function of air exchange rate and time.

$$C = C_0 e^{-(KQt/V)}$$

where C is concentration at time t, C_0 is initial concentration at time t = o, Q is the air turnover rate (ft^3/min), V is room volume (ft^3), t is time (min), K is a constant to adjust for imperfect mixing, and Q/V is the air exchange rate. Using a mixing constant of 1/2 they showed that pollutant concentrations would decay in one hour to 61 percent of orininal concentration if the air exchange rate is once per hour, to 37 percent original concentration if the air exchange rate is twice per hour, and to 5 percent if the air exchange rate is six times per hour.

These theoretical concentration decay rates (and others for different time periods) were compared with actual measurements of concentrations made after controlled indoor releases of aerosol sprays containing halogenated hydrocarbons. Decay rates of concentrations of vinyl chloride and Freon 12 in a closed room showed concentration decay patterns approximately the theoretical pattern in form. The decay of vinyl chloride roughly paralleled that of Freon 12, suggesting that vinyl chloride was chemically stable during the periods of measurement (up to 2-1/2 hours).

When hairspray and deodorants were released the concentrations in the breathing zone during spraying were 122.7 ppm for vinyl chloride and 62.1 ppm for Freon 12. One hour later both concentrations had reduced to about 0.1 ppm. Using an insect spray the immediate breathing zone concentrations were 380.1 ppm for vinyl chloride and 466.4 ppm for Freon 12. One hour later the concentrations were 0.8 ppm and 0.9 ppm respectively [86].

These authors also reported upon concentration of perchloroethylene used in aerosol spot removers, estimating possible concentrations as high as 100 ppm immediately following spraying. They also noted the occurrence of carbon tetrachloride in an indoor residential environment near a solvent recovery plant, finding a peak measurement of 90 ppm - peak duration was not specified [86].

4.7 PARTICULATES

Indoor particulate behavior investigations have sought not only to report mass-weight concentrations but to describe the particles by their origins and chemical constituents.

Primary particulates are particles injected directly into the atmosphere as a result of chemical or physical processes peculiar to any emission source. Common sources are windblown soil, industrial emissions, and combustion systems. Examples of typical primary particulates are pollen, fly ash, the mixtures of combustion wastes often called "soot," and the mixtures of various particulates called "dust." Secondary particulates are formed as a direct result of atmospheric reactions involving gaseous species such as SO_2, NO_x, O_2, NH_3, H_2O, and hydrocarbons [209]. They range from 0.01 to 1.0 μm in size and are typically sulfates, nitrates, or hydrocarbons. The classification of particulates as primary or secondary is helpful in determining the origin of ambient particulates, in describing their behavior, and in determining control strategies. This classification however is of limited value in describing indoor pollutant behavior and appears not to have been used to characterize airborne particulates inside buildings.

Particle size characteristics are important in the study of particulate behavior. Particulates may consist of "a cluster of several molecules or they can be as large as visible dust kernels" [209]. Particles larger than 5 μm can be sized directly using screens or sieves which measure the geometric or physical size of particles, according to Fennelly [209]. Impingers are used to determine the aerodynamic equivalent diameter of particles in the size range of 0.1 to 5.0 μm. Finally, particles smaller than 0.1 μm must be monitored using the optical or electric properties of the particle [209].

The importance of particle size to indoor particulate behavior is twofold. First the size of the particles determines both their ability to infiltrate and diffuse into the indoor environment and their transport and decay within rooms and floors of dwellings and buildings. Secondly, the size of particles determines the extent to which they pass various stages of the human respiratory system. Fennelly [209] points out that primary particulates ("particulates that are injected directly into the atmosphere") comprise the bulk of particles greater than 2.0 µm and that secondary particulates ("formed as a result of atmospheric reactions involving gaseous species") comprise a large portion of the particles and behave much like a gas by being subject to Brownian movement, following fluid streamlines and capable of coagulation and condensation.

The chemical behavior of particulates may be determined by an analysis of individual particles and by the types of gases which can absorb onto the particulates surfaces. Investigations of trace metals in fly ash and urban air indicate that such toxic elements as Pb, Mn, Cd, Tl, As, Ni, and S increase in concentration with decreasing particle size [155, 381]. Tables 25 and 26 adapted from the work of Lee and Van Lehmden [381], which show the concentration and size of trace metal in urban air and in fly ash as a function of size, appear on the following page. This information applies to the ambient air, but would also be relevant to infiltrated ambient air entering buildings.

The constituents of particulate matter, including sulfates, nitrates, polycyclic organic matter, and asbestos, have been linked with various chronic diseases [566, 567]. There is a growing consensus that although size, shape and solubility of a particulate determine its deposition in the human respiratory system, the chemical nature of the particulate determines its toxicity.

Few studies have been conducted in indoor particulate behavior in which both the size and chemical constituents of the samples have been determined. Studies by Jacobs et al. [329, 330] of dust counts

TABLE 25. CONCENTRATION AND SIZE OF TRACE METAL PARTICLES IN URBAN AIR [181]

Metal	Concentration, $\mu g/m^3$	MMD*, μm	Particles <1 μm, Percent
Fe	0, 6-1, 8	2, 35-3, 57	12-35
Pb	0, 3-1, 2	0, 2-1, 43	59-74
Zn	0, 1-1, 7	0, 58-1, 79	14-72
Cu	0, 05-0, 9	0, 87-2, 78	16-61
Ni	0, 07-0, 11	0, 88-1, 67	28-55
Mn	0, 02-0, 17	1, 34-3, 04	13-40
V	0, 06-0, 86	0, 35-1, 25	41-72
Cd	0-0, 08	1, 54-3, 1	22-28
Be	0-0, 09	1, 95-2, 26	23-31
Cr	0, 005-0, 31	1, 5-1, 9	45-74
Sn	0-0, 09	0, 95-1, 33	28-55
Mg	0, 42-7, 21	4, 5-7, 2	17-23

* The mass median diameter (MMD) represents the approximate "average" aerodynamic particle size, i.e., 50 percent of the particles are above this size and 50 percent are below.

TABLE 26. TRACE METALS IN FLY ASH AS A FUNCTION OF PARTICLE SIZE* [181]

Element	Concentration, ppm				
	25 μm	12, 5 μm	10 μm	3, 5 μm	1, 5 μm
Al	67,000	54,300	57,300	63,600	59,300
B	300	500	500	500	500
Be	2	1	2	2	2
Cd	< 5	< 5	< 5	< 5	100
Cr	130	140	130	300	300
Cu	150	150	200	200	200
Fe	40,000	39,000	43,500	35,500	32,300
Mn	200	240	290	330	500
Ni	300	200	200	300	300
Pb	300	300	300	800	500
V	200	200	200	200	200

* Sample collected from a coal-fired steam power plant and analyzed by neutron activation and spark source mass spectrometry.

and suspended particulate, report that the mass-weight of particulate and its average size in indoor air are not significantly different from that of outdoor air. Yocom et al. [716] suggest that particulate can become enriched with soluble organic matter. Their data demonstrate that the relative enrichment of indoor particulate matter with respect to soluble organic material is a result of the generally small size of these soluble organic particles and the presence of sources for this enrichment indoors (smoking and cooking). Investigators have found that the organic portion of particulate is higher indoors than outdoors, whereas the ash content of particulate is higher outdoors [241].

Particulate resulting from cigarette smoking is no longer considered to be just a personal health hazard, but a danger, in varying degrees to the nonsmokers who occupy the same general area [486]. The Federal Aviation Administration's 1971 report on "Health Aspects of Smoking in Transport Aircraft" [662] found that cigarette smoke is the primary contaminant on passenger aircraft. Elliott and Rowe [185] reported that smoking at public gatherings leads to a five-fold increase in the average total suspended particulate matter over the normal background level. The authors also reported that where enforcement of "No Smoking" regulations is in effect there is a significantly lower level of suspended particulate matter (SPM).

The size of particulates in tobacco smoke ranges from 0.01 to 1.0 um [208]. This is of particular concern since particles in this range can be deposited in the lung. The particulate matter in tobacco smoke remains suspended and, like a gas, diffuses within an indoor environment. It has also been reported that the particulate concentration level which results from the "smoking of one cigar completely overcomes the effect of the filtration device (electrostatic filter) for at least one hour and the counts are still well up at the end of two hours" [382].

After smoking takes place there is a high concentration of SPM in the room which decreases with time, as the ventilation system and other mechanisms remove particulates. The rapid rise in the concentration and the slow removal of particulates can be averaged to obtain the decay rate in terms of a half-life. Because of the differences in half-lives between CO and SPM, CO cannot be used as a tracer for SPM without the use of a correction factor [486]. Also the use of CO as a tracer to define the behavior of cigarette smoke was found to be unsatisfactory by Hinds and First [296]. The authors determined that nicotine was a better tracer since tobacco is virtually the only source of nicotine and it is the second largest component of tobacco smoke particulates. Penkala and de Oliveira [486] found that the half-life of SPM is 42.8 min from cigarettes and that the smoking of one pack of cigarettes per day will raise the particulate concentration in occupied spaces above the ambient air quality annual standard (75 $\mu g/m^3$), and above the 24-hour standard (260 $\mu g/m^3$) in all but the best ventilated conditions. Bridge and Corn [89] also concluded that suspended particulate matter generated from cigarette and cigar smoking can reach concentrations considered to be excessive in comparison with the annual ambient air quality standard arithmetic mean. A later study by Hinds and First [296] obtained results which were lower than those of Bridge and Corn, who did not allow for evaporative and diffusive losses to surface areas. Hinds and First concluded that "although tobacco smoke concentrations often exceed the annual average air quality standard for clean air, these levels would not be expected to produce the strong public reaction to tobacco smoke that has developed in the past few years. This observation suggests that annoyance from tobacco smoke is caused by factors other than the average concentration of particulate matter in the indoor atmosphere. For example, annoyance may be a response to peak concentrations of tobacco smoke that are likely to be much greater than the average values" [296].

4.8 OTHER POLLUTANTS

There have been several studies of mercury vapor behavior in buildings, examining sources such as fungicides in latex wall paints, broken mercury thermometers, or laboratory emissions (from incomplete cleanup of spilled Hg) [217]. A study on the mercury emissions from latex paints [570] reported interior background levels of mercury of 0.32 ug/m^3. The same study found Hg levels during painting (latex print) of 4.5-12 ug/m^3 with a decay rate after 10 days of 3.5×10^{-3} percent/day. They estimated that the mercury vapors would last for approximately seven years [570].

Pesticides have been reported in various concentrations in the indoor environment attributed to both infiltration from the ambient air, and indoor use of common household aerosol insecticides. Davies et al. 1975 [151] reported average DDT concentrations of 129 ppm from samples taken from 15 homes. In one home there was a peak level of 916 ppm of DDT. Davies also reported levels of Dieldrin at 29.3 ppm and Methoxychlor of 212 ppm. Another mechanism for pesticide contamination of the indoor air can take place as a result of the vaporization of pesticides which have been applied in a liquid or solid state. Leary et al. [379] found concentrations of DDVP as high as 0.13 mg/m^3 in the air of Arizona homes several days after installation of polyvinyl chloride resin strips. This level declined to 0.08-0.09 mg/m^3 between two and four weeks after installation.

4.9 OVERVIEW OF RESEARCH IN THE DISTRIBUTION AND BEHAVIOR OF INDOOR AIR QUALITY

The concentrations, residence times and decay rates of the major ambient air pollutants, SO_2, NO, NO_2, CO, O_3 and suspended particulates, have been studied in indoor environments by a number of researchers. The role of building ventilation in establishing indoor/outdoor concentration ratios has been investigated. Data are to some extent available to assist in deriving correlations and testing the validity of models which describe the physical behavior of all these pollutants as they enter, remain in, and leave the indoor air environment. The data available will permit only gross generalizations concerning the movement of pollutants (i.e., pollutant concentration gradients) within structures. Researchers have measured their concentrations "inside" and "outside" the structure; sometimes "in a bedroom" or "in a kitchen." In some cases, distances are given between pollutant sampler locations and potential pollutant sources, but the amount of concentration data precisely located in space and time with respect to measured emissions sources in the indoor environment is small.

There are research data on the indoor decay of introduced ambient reactive pollutants, which show correlations between removal of pollutants from the air and such elements of the indoor environment as temperature, humidity, presence of other reactive pollutants in the air, room volumes and room surfaces. The data show positive correlations between pollutant decay and these elements. There appears not to have been research dealing with the formation in the indoor environment of measurable quantities of such secondary pollutants as sulfates, nitrates and nitrosamines. In general, the area of chemical transformation and fate of indoor pollutants has not been addressed in depth from a chemical modeling point of view; an exception has been the indoor behavior of ozone as studied by Shair and others [561, 171].

Tobacco smoking has been the subject of much investigation. There are data on pollutant emissions by species and quantity, and there is a substantial body of measured indoor CO concentration and particulate data associated with information about smoking as a source.

There is considerable literature dealing with the presence in indoor air of other pollutants, among them halogenated hydrocarbons, asbestos, mercury and other trace metals. But reports of measured indoor air concentrations of these pollutants, or of their measured source strengths, have not appeared often in this literature research.

Section 5.0

MONITORING TECHNOLOGY

Indoor air pollution monitoring must rely heavily on ambient air and industrial hygiene sampling technology. As these methods are incorporated into indoor air sampling programs, changes must be made in order to meet more stringent noise and space requirements. Ambient air samplers such as hi-vols will have to be replaced by quieter and smaller particle samplers. Additionally, for indoor sampling, consideration of the volume of air removed from the structure must be taken into account in order to avoid introduction of error with respect to the natural ventilation rate of the structure. For example, a structure with 30,000 ft^3 volume may have a natural ventilation rate of 250 ft^3 per min. Sampling air from this structure for test purposes through several sampling lines may amount to as much as 12 to 15 cfm which must be considered while developing indoor-outdoor numerical models.

Many other parameters relevant to sampling cannot be overlooked. Those which appear to be of greatest importance are listed below:

- Sampling line material
- Retention time within sampling line
- Reaction of pollutants within sampling line
- Response time of the continuous monitors
- Sampling pump and manifold materials

- Avoidance of problems resulting from physical constraints, i.e., water vapor condensation during winter sampling periods
- Strict quality assurance procedures.

The purpose of this phase of the survey was to gather information on the sampling for and analysis of pollutants expected to be found indoors in dwellings and public buildings. Methods of sampling and analysis and related information such as detection limits and collection efficiencies were sought. A literature search produced much information concerning the monitoring of the six primary (criteria) pollutants was readily obtained. Also examined were literature articles detailing procedures for collection and analysis of the following nonprimary pollutants:

- Metals (in general) in suspended particulate
- Cd in particulate
- Al in particulate
- Pb in settled household dust
- Hg (particulate and gaseous)
- Aerosol propellants
- Ammonia
- Pesticides
- PAN
- Soiling particulate.

Information on the available monitoring technology for various indoor air pollutants is presented in the following pages, categorized by pollutant species.

5.1 SULFUR DIOXIDE AND SULFATES

5.1.1 Sulfur Dioxide

Sulfur dioxide (SO_2) is a common atmospheric pollutant produced by combustion processes. Fossil fuels, such as coal and petroleum, contain elemental sulfur, and when the fuel burns, the sulfur is converted to sulfur dioxide and to a lesser degree, sulfur trioxide. Since fossil fuels are burned abundantly in the United States to heat buildings and to generate electric power, pollution of the atmosphere with the oxides of sulfur is widespread and is especially prevalent in cities. Petroleum refineries, smelting plants, coke processing plants, sulfuric acid manufacturing plants, coal refuse banks, and refuse burning activities are also major sources of sulfurous pollution. Indoor concentrations of SO_2 have been found in numerous studies to be related to that of the outside air [27, 65]. Yocom has shown that furnaces in homes heated by coal are also a possible source of high indoor SO_2 concentrations [714, 716]. Recent work by Hollowell found elevated indoor SO_2 levels associated with gas stoves [308].

Many instruments capable of continuously measuring ambient concentrations of SO_2 are available commercially [375, 608]. These instruments are based on different measurement principles with the most common principles of operation being conductometric and gas chromatographic [375, 608]. Continuous analyzers using these principles have been used for many years and have been thoroughly tested under field conditions [65].

Indoor-outdoor comparison measurements requires locating individual monitors at each sampling point, representing a substantial equipment investment, and resulting in multiple servicing and space requirements with a lack of confidence in the comparison of data from point to point [691]. The use of a single instrument with a multiple sequencing device has been found to be the most practical and economical approach to the problem [715, 308, 691]. Yocom describes a unique mobile measurement system capable of sampling at four locations using a single instrument for each parameter [715, 716, 691]. This system consisted of four continuously purged sampling lines with an integrating chamber and solenoid switching valves. By drawing the instrument's air sample from the integrated sample chamber, retention time was reduced to approximately two seconds. The short retention time allowed four 5-minute samples to be sequentially measured with a conductometric SO_2 analyzer every 20 minutes.

In studying combustion-generated pollution in six homes, Hollowell used an UV fluorescence SO_2 analyzer in conjunction with a sequential sampling system to make indoor and outdoor measurements [308]. The sample intake for the gas and electric stove measurements was placed in the breathing zone 1.5 meters above the floor near the front of the stove.

Bubblers consisting of absorbing reagent and air flow measuring devices have been used extensively in ambient air and industrial hygiene to collect integrated SO_2 samples. These methods have been incorporated as standard measurement techniques by both the Environmental Protection Agency and the National Institute of Occupational Safety and Health [203, 649].

Dynamic calibration of sulfur dioxide monitors is considered to be the most desirable technique as opposed to calibration by static means. Dynamic calibration is normally accomplished by employing one of two basic techniques:

- Dilution of sulfur dioxide gas mixtures with "zero" air followed by analyses employing the EPA Reference Method [182].
- The use of NBS certified sulfur dioxide permeation tubes and related zero air dilution apparatus [475, 541, 542].

The technique employing dilution of the standard gas mixture and simultaneous analyses by the reference method requires considerably more effort and time as compared to the use of the permeation tube technique. Both methods can result in the same accuracy and precision, but due to the increased number of operations inherent to the dilution technique the permeation tube methodology has received wider use.

5.1.2 Sulfates

Airborne sulfates, like nitrates, have both natural and man-made sources. Natural producers include volcanic action and suspension of magnesium sulfate from sea spray [208]. Combustion of sulfur-bearing fuels and smelting of sulfide ores are major non-natural sources [550]. Combustion would seem to be the major indoor-generated source of sulfates; intrusion of external air would also contribute.

One study, which included particulate sulfur, measured it by X-ray fluorescence [308]. Studies of outdoor suspended particulate used the same method of collection as for nitrate, filtration followed by water extraction. The analytical methods are those for sulfate in water, and include precipitation as barium sulfate, barium sulfate turbidimetry, specific ion electrode, and methythymol blue colorimetry [20, 475, 378].

5.2 CARBON MONOXIDE

Carbon monoxide (CO) is by far the largest single gaseous pollutant found in urban atmospheres [557]. It is a product of the incomplete combustion of all types of carbonaceous fuels. Indoor CO is generated by combustion processes such as smoking, heating, and cooking [715]. Being nonreactive, CO readily penetrates all structures and indoor concentrations are strongly influenced by that of the ambient air outside.

Of the six methods used to measure carbon monoxide (Gas Chromatography with flame ionization detector, Dispersive Infrared, Nondispersive Infrared, Catalytic Oxidation, Amperometric, and Mercury Vapor), the nondispersive infrared (NDIR) technique is the most popular instrument used [375]. This instrument is also the basis of the reference method specified by the Environmental Protection Agency [203]. Yocom used a nondispersive infrared (NDIR) instrument in conjunction with a special sequencing sampling system previously described to measure pollutant profiles inside and outside of structures [715, 716, 691].

In his study of indoor and outdoor concentrations, Derham et al. used two NDIR instruments to simultaneously measure indoor and outdoor

CO concentrations [158]. One instrument was located in a room of a laboratory building, the other at the ventilation intake duct in the same building. By this method Derham insured that the concentration of the air actually entering the vent system would be measured. Thompson incorporated a continuous NDIR analyzer and grab samples to do comparative measurements of indoor-outdoor CO concentrations for 11 buildings in the South Coast Basin of California. The NDIR analyzer was located in a small house trailer near the building to be monitored and was used to continuously measure the outside air. Grab samples were then collected in Mylar bags from different locations within the building and brought to the NDIR analyzer to determine CO concentrations.

The nondispersive infrared analyzer has also been found to be a reliable instrument in the measurement of CO concentrations on board nuclear powered submarines [529]. While most studies on indoor CO levels were conducted on residential homes or private buildings, Elliot and Rowe carried out CO measurements in an area during public gatherings [185]. Measurements of CO were carried out by use of indicator tubes This technique provides a simple and economical method of sampling but is only useful for spot-checking CO concentrations. With a sensitivity of ± 25 percent this technique is not recommended for indoor monitoring.

There are a number of ways of preparing CO gas standards [548], for dynamic calibration of carbon monoxide analyzers. Most methods involve dilution of CO with a nonreactive gas of zero or known CO content. This can be done using pressurized tanks [20] for large amounts or plastic bags [548] if lesser amounts of standard gas are required.

Standard gases are also commercially available and any concentration can be specified and certified by the manufacturer [682].

There have been instances where purchased CO standards have been in error [410]. For this reason it is important to compare standards from independent sources to make independent determinations of the CO concentration.

Presently, standard gases contained in specially treated aluminum cylinders under pressure are in the widest use.

5.3 CARBON DIOXIDE

Carbon dioxide, a normal component of air, is a part of the carbon cycle in the biosphere. In addition to occurring naturally, it is produced in the combustion of fossil fuel. Since humans also exhale carbon dioxide during normal breathing, indoor concentrations have been found to be higher than those found outdoors [65].

CO_2 is normally not considered a pollutant and very little work has been done in this country concerning indoor measurements. Stern describes a nondispersive infrared spectrometer similar to those used for CO measurements as a reliable method of continuously measuring CO_2 concentrations [606]. Integrated CO_2 sampling methods where the air sample is bubbled through a reagent was also described. Two areas in which CO_2 is a major concern are submarine atmospheres and atmospheres in manned space craft. In both cases, a system employing mass spectrometers has been developed to continuously measure CO_2 along with other gases [527, 530, 529].

Such multi-gas sensors could be very useful in future indoor air pollution work.

There are a number of ways of preparing CO_2 gas standards [548] for dynamic calibration of carbon dioxide analyzers. Most methods involve dilution of CO_2 with a nonreactive gas of zero or known CO_2 content. This can be done using pressurized tanks [20] for large amounts or plastic bags [548] if lesser amounts of standard gas are required. Standard gases are also commercially available and any concentration can be specified and certified by the manufacturer [682].

There have been instances where purchased standards have been in error [410]. For this reason it is important to compare standards from independent sources or make independent determinations of the CO_2 concentration.

Presently, standard gases contained in specially treated aluminum cylinders under pressure are in the widest use.

5.4 NITROGEN OXIDES AND NITRATES

5.4.1 Nitrogen Oxides

Oxides of nitrogen are one of the most important groups of atmospheric contaminants in many communities. They are produced during the high-temperature combustion of coal, oil, gas, or gasoline in power plants and internal combustion engines. The combustion fixes atmospheric nitrogen to produce the oxides. At these temperatures, nitric oxide forms first and in the atmosphere it reacts with oxygen and is converted to nitrogen dioxide. While this oxidation is very rapid at high concentrations, the rate is much slower at low concentrations. In sunlight, especially in the presence of organic material as typified by Los Angeles-type photochemical smog, the conversion of nitric oxide to nitrogen dioxide is greatly accelerated.

Indoor concentrations of NO_x have been found to be related to indoor combustion sources used for heating and cooking and to the outside ambient concentrations [308, 691, 431, 385, 627, 158].

In order to make comparison measurements between indoor and outdoor NO-NO_x gas analyzers [158] simultaneous measurements were taken by locating one analyzer in a room of a laboratory building and the other next to the ventilation intake duct on the roof of the same building. It was felt that this method assured that actual concentrations of NO-NO_x in the air entering the vent system would be measured. In this way the relation between NO-NO_x entering the building and the indoor concentrations could be compared.

Hollowell, in making comparative measurements, utilized a single chemiluminescence analyzer to measure $NO/NO_2/NO_x$ [308]. By locating the instrument near the indoor and outdoor sampling locations and using a multi-point sampling system, samples could be collected at both locations. The sample intake for gas and electric stove measurements was placed in the breathing zone approximately 1.5 meters above the floor near the front of the stove. Measurements to study the effects of the heating systems were made with the sample intake in the bedroom approximately 1 meter above the floor.

Yocom determined indoor-outdoor pollutant profiles with a single chemiluminescent analyzer and a mobile multiple point sequential measurement system [715]. Sample lines were run from the equipment to four sampling stations. One station was located outside the structure, the other three being in the kitchen, living room and bedroom. Sample intakes for each station were placed in the breathing zone, between 4-1/2 and 6 feet above the floor. The sample inlet in the kitchen was placed adjacent to the stove. By sequentially taking 5-minute samples at each location short-term effects of stove use on indoor air quality and pollutant behavior within the structure could be studied.

When making comparisons of indoor-outdoor NO and NO_2 concentrations for 11 buildings in the South Coast Basin of California, Thompson made use of both continuous and grab samples [627]. A continuous NO_2-NO_x analyzer along with other instruments and accessory equipment were installed in a small house trailer. The trailer was set up near each building to be sampled and the NO_2-NO_x monitor used to continuously measure the outside ambient air. Indoor grab samples were then collected in Mylar bags and brought to the NO_2-NO_x monitor for analysis. In studies where NO_x emissions from natural gas-fired appliances were studied, continuous chemiluminescent NO_x analyzer and 24-hour integrated bubbler samples, determined with the Jacobs-Hochheiser method, were used [431, 385].

Dynamic calibration of oxides of nitrogen monitors, specifically chemiluminescence analyzers which are in most prevalent use today, are normally calibrated by one of the three following techniques:

- Dynamic dilution techniques employing certified concentrations of NO or NO_2 in nitrogen contained in treated aluminum cylinders under pressure. With this technique the NO or NO_2 gas is diluted with zero air and the resulting mixture is introduced to the monitor through a manifold system [182]. With this technique for NO gas, there exists the possibility of oxidation of NO to NO_2. Should this reaction occur the amount of NO oxidized to NO_2 would be detected by the NO_2 analyzer.

- Certified NBS NO_2 permeation tubes and a related dilution system has also found broad usage for the dynamic calibration of nitrogen dioxide monitors.

- Gas phase titration [186] employing certified NO gas concentrations as one of the gaseous reactants and a stable source of ozone as the other is employed to produce varying levels of known concentrations of NO and NO_2, based on the following reaction:

  $$NO + O_3 \rightarrow NO_2 + O_2, \ K = 1 \times 10^7 \ mole^{-1} \ sec^{-1}$$

  Both NO and NO_2 monitors can be calibrated simultaneously with this technique.

Of the three techniques referenced above, the gas phase titration is at present being used more frequently due to the fact that both parameters, i.e., NO and NO_2 can be calibrated against a standard which is traceable to NBS.

5.4.2 Nitrates

Several sources contribute nitrate to the environment. Natural sources include oxidation of atmospheric nitrogen by soil bacteria and lightning, and discharge by volcanic action [557]. Humans add nitrates by combustion processes and application of fertilizer. Combustion appears to be the major source of indoor nitrate; it is possible that bacteria in household plant soils oxidize combustion generated NO_x as well as elemental nitrogen [52].

No major studies on nitrates in indoor air have been published. Some work has been done on their presence in fugitive dust [495].

Generally, particulates are collected on a filter medium, and the water soluble portion leached out. Nitrate in water can be determined by the phenoldisulfonic acid (PDSA) method, the brucine method, or by use of a specific ion electrode [19, 25, 475]. The methods have different sensitivities and interferences, so the choice must be made according to expected levels and other ions present.

5.5 PHOTOCHEMICAL OXIDANTS

Ozone is one of the principle oxidants found in photochemical smog - a major air pollution problem arising from atmospheric reactions of gases derived from the combustion of organic fuels. Emissions from motor vehicles are a prime factor in the formation of photochemical smog in virtually all parts of the country. Other factors which contribute to smog formation are the combustion of fuels for heat and electric power, burning of refuse, evaporation of petroleum products, and handling and use of organic solvents. Ozone is also formed naturally by electrical discharge (lightning) during thunderstorms and the reaction of ultraviolet on oxygen molecules.

Very little ozone is generated within a structure; it is generally brought in with the outside air [626, 627]. Being highly reactive, ozone levels inside structures were generally found to be 1/2 to 2/3 of those in the ambient air outside.

Although a considerable amount of work has been done in measuring outdoor ozone concentrations, very few indoor measurements have been made. This is probably due to the fact that ozone is highly reactive and therefore is easily removed from the indoor air [626, 158, 627].

Thompson, in his measurements of ozone levels inside of a hospital, used an ozone meter based on the electrolytic Brewer cell [626]. Calibration of this instrument was done by comparison of concentration simultaneously measured with a solution of buffered potassium iodide. A further check of the instrument's accuracy was made by comparing its results to measurements obtained by the absorption of a standard atmosphere of ozone in a long path infrared spectrophotometer. Details of measurement locations were not presented in the paper. In a later study, Thompson used two of the previously described ozone meters to make comparisons between indoor and outdoor ozone concentrations [628].

Ozone, while not being considered an indoor generated pollutant, was measured in a study on combustion-operation indoor air pollution conducted by the Lawrence Berkeley Laboratory [308]. A UV absorption unit was used to measure any ozone that might be produced under typical occupancy conditions of cooking and heating. As expected, except for a small increase in ozone during usage of the electric stove, no combustion-generated ozone was found.

Analyzers employing chemiluminescence, electrochemical and spectrophotometric gas phase techniques have been used to continuously monitor ozone. Only analyzers that meet EPA Ambient Air Quality Reference and Equivalent method standards should be employed in indoor air monitoring [65].

Dynamic calibration of ozone analyzers requires a stable source of ozone. Such a source has been developed [78] and is commercially available. The ozone generator (source), however, requires calibration. Three techniques are presently in wide use. They are:

- The Neutral Buffered Potassium Iodide method [682]
- The gas phase titration technique employing NBS certified NO gas as the reference material
- The reverse gas phase titration technique employing NBS certified NO gas as the reference material and related apparatus for complete reaction of O_3 with the NO_2 which is initially formed [186].

Of the three techniques stated above, the Neutral Buffered Potassium Iodide method is employed most frequently, since the other techniques require a nitrogen oxide analyzer as an integral part of the calibration apparatus or other special gas apparatus for the reaction chambers. In those instances where both ozone and nitrogen oxide analyzers are to be calibrated, the method of choice is the gas phase titration.

5.6 HYDROCARBONS

5.6.1 Total Hydrocarbons

Hydrocarbons are a group of compounds made up of carbon and hydrogen atoms. These are emitted during the incomplete combustion of all fuels (including rubbish and agricultural field wastes), but automobile exhaust is the major source. Hydrocarbons and other organic gases are also expelled during the production, refining, and handling of gasoline and from such manufacturing operations as industrial dryers and ovens, and furnaces used for baking paints, enamels and printing ink. Indoor generated sources are heating, cooking, and solvent usage [158].

Sampling of indoor air for HC presents no unusual problems. While there are different monitoring methods available for HC, the method recommended is that specified by the Environmental Protection Agency. This method involves filtration through a 3 to 5 micron filter before injections of the sample into a flame ionization detector. To determine nonmethane hydrocarbons, an aliquot of the same sample is introduced into a stripper column which removes water, carbon dioxide, and hydrocarbons other than methane. The remaining methane is then measured by the flame ionization detector. The difference between total HC and methane gives the HC that is of concern as an air pollutant [607]. The non-dispersive infrared spectrometry technique based on the broadband absorption in the wavelength region of a few micrometers has also been used for THC measurements. This technique is subject to interference because other bases (H_2O, CO_2) absorb at the wavelength of interest [375]. Gas chromatography serves as a useful tool in HC measurements, in that individual hydrocarbon components can be identified [375].

Dynamic calibration of total hydrocarbon and methane monitors can be performed by several techniques. These techniques include dilution systems employing the desired hydrocarbon and a zero gas for dilution air [645], a permeation tube containing the specific hydrocarbon which has been gravimetrically calibrated [475] and an appropriate dilution apparatus, or inert plastic bags filled with known volumes of zero air and the appropriate hydrocarbon [182]. Calibration gases are commercially available and their content can be specified with respect to concentration and certified by the manufacturer to within ± 2 percent. Recently [682] these standard gases have been shown to be stable for long periods at low concentrations, which enables one to employ the gas directly from the cylinder without dilution.

This latter source of calibration gas, for low molecular weight hydrocarbons (C_1 thru C_6), is being employed most frequently at present.

5.6.2 Organic Solvents and Trace Organic Materials

Organic solvents are found in most homes: for example, various cleaning fluids such as perchloroethylene, lighter fluid, and fingernail polish remover contain assorted aliphatic, aromatic, and chlorinated components. In addition, hobby materials such as model airplane cement and varnish contain similar materials. Some solvents likely to be encountered are perchloroethylene, toluene, and naphthas. Gasoline fumes can penetrate from an attached garage.

Organics other than solvents are found in many homes. Primary examples are the Freon propellants in spray cans, various insecticides, and nicotine from smoking.

Two studies, by Collins et al. and Compton et al., investigated pesticides in homes [133, 136]. The former involved collecting vapor in ethyl acetate, followed by concentration and analysis by gas chromatography. The second used collection in several media, followed by a series of aqueous and organic extractions to separate pesticides into groups. Two other studies involved sampling and analysis for chlorofluorocarbons (Freons); only Hester's included sampling and analysis [280, 86]. His group collected air in standard glass sampling tubes and analyzed it by gas chromatography. Detection limits of Freon 11 and 12 were 5-10 ppt and 100-200 ppt, respectively. Two other groups studied nicotine in indoor air [296, 312]. Hinds collected tobacco smoke on Millipore filters, extracted the nicotine with water, and analyzed by gas chromatography. Horning's group analyzed air with a mass spectrometer.

One of the most widely used methods for organic vapors in air is collection in tubes of activated charcoal, desorption into an organic solvent, often carbon disulfide, and analysis by gas chromatography. The method has been used outdoors and in industrial applications [645, 550, 514, 690, 362]. Elfers achieved a detection limit of 1-10 ppb when sampling 250 l of air through 13 cm of charcoal [183].

Studies in the laboratory have determined the collection efficiencies of chromosorb 12, followed by hexane-acetone extraction, and ethylene glycol with a benzene extraction [624, 423]. Both sets of analyses were made by gas chromatography.

The major problem involved with any pesticide analysis is contamination; the chromatograph must almost always be used only for pesticides. The same restriction applies to the sampling and analysis of Freons. The analysis of the more common organic solvents is not so difficult because their levels are usually above the noise of a slightly dirty chromatograph. Large samples can be taken by using long (15 cm) charcoal tubes and high sampling rates, so long as the rate is not too high to allow adsorption to occur.

5.6.3 Aldehydes

Aldehydes are a class of organic compounds, members of which may be present in the indoor atmosphere. Some aldehydes are produced from incomplete combustion during cooking; formaldehyde is a part of the glue used as chipboard binder and is released from it over a period of years [28].

Indoor studies of formaldehyde have involved sampling about 50 l of air through a bubbler system into chromatropic acid solution, followed by color development and spectrometric analysis [28, 606, 9]. Anderson's group attained a detection limit of 0.1 mg formaldehyde per m^3, with a reproducibility of ± 5 percent at 1 mg/m^3 [28].

Another procedure for aldehyde determination, which has not been used on indoor air samples, is the MBTH (3-Methyl-2-Benzothiazolone

Hydrazone Hydrochloride) method [276]. It involves sampling into a solution of MBTH, followed by color development and spectrometric measurement. A 50 l sample has a sensitivity of 0.04 ug/m^3 aldehydes expressed as formaldehyde.

The MBTH method appears to be better than the chromotropic acid method. It is more sensitive, and responds to all water soluble aliphatic aldehydes; the chromotropic acid method responds to only formaldehyde. The two procedures are about equally complex as far as laboratory work. The MBTH method is not 100 percent efficient; its efficiency can be determined under the exact conditions to be used.

Further research would include studies of collection efficiencies under various flow rates and sampling times for both methods.

5.7 PARTICULATES

Particles of solid - and occasionally liquid - matter in the air constitute an important portion of polluted community air in most cities and towns in the United States. These so-called particulates may be either so large that they rapidly settle to the ground or they may remain suspended in the air until they are removed by such natural phenomena as rain - or until they are inhaled by people. Particulates may be quite complex in their chemical composition. The organic materials found in airborne particles may contain aliphatic and aromatic hydrocarbons, acids, bases, phenols, and other compounds. Airborne particles may also contain any of a wide range of metallic elements; those most commonly found are silicon, calcium, aluminum iron, magnesium, lead, copper, zinc, sodium, and manganese. Sources of particulates include such activities as fuel combustion, various manufacturing and processing operations - including production of steel, cement, and petroleum products, and open burning and incineration of refuse. Particles found indoors which may be carried in with ambient air or generated indoors are from cigarette smoking and resuspension of dust by human activities (use of paper products, turning pages in books, standing up, sitting down, and changing and brushing clothing [226]). Cooking, heating, cleaning, and use of aerosol sprays are also known sources [716, 308]. Buchnea and Buchnea report that air conditioners which normally remove particles may generate aluminum oxide particles of their own [94]. Indoor particle concentrations may be measured continuously or as integrated time-averaged samples. Most researchers prefer to use the integrated method where particles are collected (filtering, impactor, etc.) and then gravimetrically measured. The main advantage of this method is that it is inexpensive and that particles can be subjected to chemical and physical analysis at a later time. Particle concentrations are normally presented as total suspended particles (TSP) or respirable particulates.

5.7.1 Total Suspended Particulate

One of the most basic instruments for collection of total suspended particulates (TSP) is the hi-volume air sampler. This instrument, which pulls an air sample through an 8 x 10 inch filter at a flow rate of 30 to 50 cfm, is widely used for ambient air sampling. Elliot and Rowe used a hi-vol for making TSP measurements in an arena during public gatherings [186]. One problem that Yocom and Thompson found in their studies was that the noise level of hi-vols was unacceptable in occupied buildings [715, 626]. In both cases special filter collection devices were built. Yocom used a 4-inch filter holder with a Type A glass fiber filter [715]. The filter holder was connected to a vacuum line attached to a pump. By locating the pump in a trailer outside the building the indoor noise was minimized. Samples were collected over 12-hour periods with approximately 100 cubic meters of air being sampled for each period. In Thompson's case, a 9 cm diameter plastic Buchner funnel was modified to use discs of the same diameter cut from glass-fiber hi-vol filters [626]. A gas meter and rotary pump were used to provide an air flow of 0.47 dubic meters per minute through the filter.

When particles are collected for chemical analysis, care must be taken to select the proper collection media. In the study of combustion-generated indoor air pollution, Hollowell selected two types of filters to be used to collect particles for chemical analysis [300]. For elemental composition by X-ray fluorescence a 1.2 NM pore size cellulose filter was selected. Particle samples were collected on a 47 mm filter at a flow rate of approximately 70 lpm for 30 minutes. A Selas Flotronics 5.0 NM pore size filter was used to collect particles for ionic species analysis by electron spectroscopy. A flow rate of 70 lpm was used for a two-hour sampling period.

5.7.2 Respirable Particulate

In order to sample for respirable particulate some mechanisms must be used to separate the respirable size particles from the total particle loading. In his first attempt at measuring respirable particulates, Yocom used a polyurethane prefilter in accordance with the method of Roesler [524]. Additional work on size discrimination was carried out with two cascade impactors. This method proved to be effective in determining the respirable size fraction of the TSP. Cascade impactors were also used by Desaedeleer to collect respirable size particles for analysis by proton-induced X-ray emissions (PIXE) [161].

The Dichotomous Sampler [488] is designed to sample airborne particles and classify them into two size fractions. The heart of the sampler is a two-stage virtual impactor whose principle of operation is analogous to that of an inertial impactor; however, the problems of particle bounce and shattering are eliminated. Particles above the cut-point size flow directly through nozzles of two stages and are collected on a filter at a rate of 1/50 of the sampling flow rate. The major fraction of the air is deflected around the nozzles of each stage and flows through a second filter where the particles smaller than the 50 percent cut-point of the sampler are collected. The primary advantage of the sampler is that the particles are uniformly deposited on low mass filters, which is most suitable for the assessment of their mass and chemical composition.

Fuchs, in his review of aerosol sampling, expressed concern that sampling methods used may not give a true representation of the air sampled [225]. He suggested a spherical probe tip whose surface was pyramids, points out, so there are no flat surfaces facing out.

When the same problem was examined by Breslin it was found that an open face filter of the type normally used to collect indoor air samples sampled correctly in calm air for the normal range of operation [83]. While open face filters may be used for calm air, sampling directly in air streams from ducts, air conditioners, or furnaces presents a different problem. In order to get a representative sample from a moving air stream, isokinetic sampling must be undertaken. Gieseke, in work performed on techniques for evaluations of airborne particulate matter, developed a sampling probe for use in sampling return air ducts [238]. With this method, air being sampled moves into the probe at the same velocity with which it leaves the duct allowing a representative sample to be collected. Three probes were used, two for collecting TSP on filters and one for particle sizing with a cascade impactor.

Many indoor particulates are generated by activities of people and the concentration that a person may be exposed to during the day is often much higher than that of the average indoor air. This would be particularly true for housewives who are constantly being exposed to dust from cleaning and cooking, while the overall 8 to 12 hour average concentrations in the house may remain low. Personal monitors for respirable particulate have been shown to give good agreement with other measurement methods and should prove to be a useful tool in health effect studies [177].

One type of gravimetric sampling system which separates respirable and nonrespirable dust consists of a portable pump with an elutriator and filter in which the dust is collected. The nonrespirable dust is collected in the cyclone (elutriator), and the respirable dust in the filter.

The elutriator and filter are fastened to the person's clothing near their breathing zone. In this manner the quantity of dust that a person would actually breathe throughout the day can be measured.

5.7.3 Trace Metals

Many metals can be found in the home. Some, for instance lead, primarily enter from outdoor air. Others can be generated indoors. Principal contaminants to be expected are lead from automobile exhaust, mercury from paint fungicides and aluminum from air conditioners [217, 94]. Specific household activities could contribute to others. For instance, antiperspirant sprays could add zirconium to the air; home shops could suspend iron, zinc, aluminum, and lead dusts.

Many methods have been used to sample and analyze for airborne metals in the home. Braman and Johnson describe a series of absorbers to selectively trap different forms of airborne mercury; each absorbent was analyzed by dc-discharge spectral emission spectrography [80]. Foote collected mercury vapor on gold screens and analyzed for it by flameless atomic ausorption [217]. Sibbett et. al [570] used an automated system employing collection on a silver screen, vaporization, and ultraviolet photometric analysis. Moffit and Kupel absorbed mercury vapor on activated charcoal and analyzed for it using atomic absorption [434]. This last method had a dntection limit of 0.02 ug in 10 l of air.

Both Berdyev et al. and Vostal et al. examined the indoor environment for lead [66, 671]. The former sampled airborne particulate and determined the lead content with the chromate method. Vostal's group, on the other hand, collected settled dust with damp paper towels, leached them with acid, and determined lead by polarography. Buchnea and Buchnea found a high percentage of aluminum in both settled and airborne dust, analyzing by 8-hydroxy quinoline precipitation [94].

Several reported studies have been made of metals in outdoor air particulate; in general, they have employed high volume samplers with either glass fiber or membrane filters, which are acid leached and the leachate analyzed by atomic absorption [430, 99, 685, 357, 321, 630]. Neutron activation analysis and X-ray fluorescence spectrometry have also been employed [246, 723, 82, 487, 304, 516, 251, 105, 517, 518]. One study, however, addressed itself to the determination of metals in low volume samples [62]. Polymer filters were acid leached and the various metals determined by flameless (graphite tube) atomic absorption spectrophotometry. The small amounts of the metals present necessitated ultrapure reagents and scrupulously clean equipment.

The procedure used by Begnoche could certainly be applied to indoor studies. It is extremely tedious, though, involving a considerable amount of acid washing of glassware, and costly ultrapure reagents. Acid leaching of whatever filter type chosen, followed by flameless or flame atomic absorption spectrophotometry, appears the most versatile procedure for a wide variety of metals [62].

Moffit and Kupel's activated charcoal mercury procedure distinguishes between particulate mercury collected on a prefilter and gaseous forms in the charcoal [434]. Collection on gold, as performed by Foote, measures only elemental mercury vapor, and Braman and

Johnson's sequential absorbents are too complicated for routine use [217, 81].

Miniaturized continuous particulate samplers ("streakers") have been developed [467] to collect particulate samples for elemental analyses employing the proton induced X-ray emission (PIXE) analytical method [467]. The streaker consists of an orifice which is driven with a synchronous motor across a strip of nuclepore filter media at a rate of approximately one inch per day. Vacuum is applied to the orifice such that the restriction through the nuclepore filter at the orifice is at critical flow conditions. The size of the orifice and the porosity of the nuclepore filter have been chosen to result in a sampling rate of 1 l/min. After sampling for one week the filter medium is removed for PIXE analyses. The proton beam can be focused on the filter material such that short (1/2 hour to 2 hour) increments of the sampling period can be analyzed for as many as 10 elements simultaneously.

5.8 CONCLUSIONS

As a result of reviewing and evaluating the information and data uncovered by this literature review, we have reached a series of conclusions relative to the most appropriate complement of methodologies and equipment currently available for indoor-outdoor pollutant monitoring. Table 27 presents our recommendations for the continuous monitoring program, including the pertinent performance parameters of each system. Table 28 lists our chosen sampling and analytical methods for indoor-outdoor monitoring of the nonprimary pollutants of major interest to this investigation.

TABLE [illegible]. CONTINUOUS MONITORING EQUIPMENT SPECIFICATIONS EMPLOYED FOR MONITORING INDOOR-OUTDOOR POLLUTANTS*

Pollutant	Principle of Detection	Concentration (ppm)		Response Time to 90% or Greater	Precision
		Range(s)	Limit of Detection		
NO	Chemilumi-nescent	0-0.5 0-1.0 0-2.0 0-5.0	0.005	100 sec.	± 1% Full Scale
NO_x	Chemilumi-nescent	0-0.5 0-1.0 0-2.0 0-5.0	0.005	150 sec.	± 1% Full Scale
CO_2	Nondisper-sive Infrared	0-2,500 0-50,000	25 500	2.5 sec.	± 1% Full Scale
CO	Nondisper-sive Infrared with flowing ref. cell	0-50	0.50	2.5 sec.	± 1% Full Scale
O_3	Chemilumi-nescent	0-0.5	0.005	15 sec.	± 2% Full Scale
SO_2	Flame Photometric	0-0.5	0.005	60 sec.	± 1% Full Scale
CH_4	Flame Ioniza-tion with Selective TCH Oxidizer	0-5 0-20	0.05 0.20	15 sec.	± 1% Full Scale
THC	Flame Ioniza-tion with Selective THC Oxidizer	0- 0-20	0.05 0.20	15 sec.	± 1% Full Scale
Wind/Speed Direction	Direction-Synchro speed-d.c. magneto	0-100 mph 0-540°	0.5 mph 5°	—	± 1% Full Scale
Temperature Relative Humidity	Bi-metallic strip-temp. Human hair	Adjust-able 0-100%	1°F 1% RH	—	± 1% Full Scale

* Ranges, Limits of Detection, Response Time to 90 percent or Greater, and Precision are specifications for particular models of continuous instrumentation and will vary among manufacturers.

TABLE [illegible]. INTERMITTENT SAMPLING AND ANALYTICAL METHODOLOGY [illegible] POLLUTANT MONITORING

Pollutant	Sampling Rate l/min	Sampling Period hrs	Analytical Method	Limit of Detection (working)
Total suspended particulates	250	24	Filtration/gravimetric	0.1 µg/m^3
Respirable particulates (3.5 µ)	50	24	Dichotomous/gravimetric Cyclone @ 9 L/M	0.1 µg/m^3
Organic vapors	0.2	24	Charcoal absorption/gas chromatography	ppb as CH_4
Aliphatic aldehydes	1.5	4	Bubbler/MBTH	1.5 µg/m^3
Ammonia	[illegible]	1	Bubbler/phenate	5 µg/m^3
Sulfates from TSP samples	150	24	Filtration/methylthymol blue	0.5 µg/m^3
Nitrates from TSP samples	200	24	Filtration/brucine	0.1 µg/m^3
Lead from TSP samples	200	24	Filtration/atomic absorption	0.005 µg/m^3
Elemental analysis atomic No. 14 through 35 plus No. 82	1	Continuous	Streaker sampler/PIXE	ppb to ppt

Section 6.0

BUILDING OCCUPANCY

The levels of indoor air pollution are in large part a function of the activities performed by building occupants, including the control and operation of the building ventilation system by the occupants. The building occupant determines, whether consciously or not, an important part of the extent to which outdoor-generated pollution is retained in the building. Many activities of building inhabitants are in themselves pollutant-generating, for example: sweeping, vacuuming, entering buildings with dirty shoes, use of aerosol sprays, smoking, and breathing. Activities, mobility patterns, various entrances and exits from the building, are all determinants of indoor pollution levels. They are also determinants of the extent of human exposure to indoor pollution, and hence of pollutant dosages and the resulting health effects.

6.1 OCCUPANCY PROFILES

A first step in the investigation of indoor air quality is to measure the duration of occupancy and the mobility of occupants. This requires making detailed estimates of frequency, intensity, and duration of human occupancy within the interior environment. Such estimates normally take the form of occupancy profiles, where the rate of occupancy is shown as a function of time. In a study performed by Seelye et al. [555] occupancy profiles are shown for apartment houses and elementary and high school buildings.

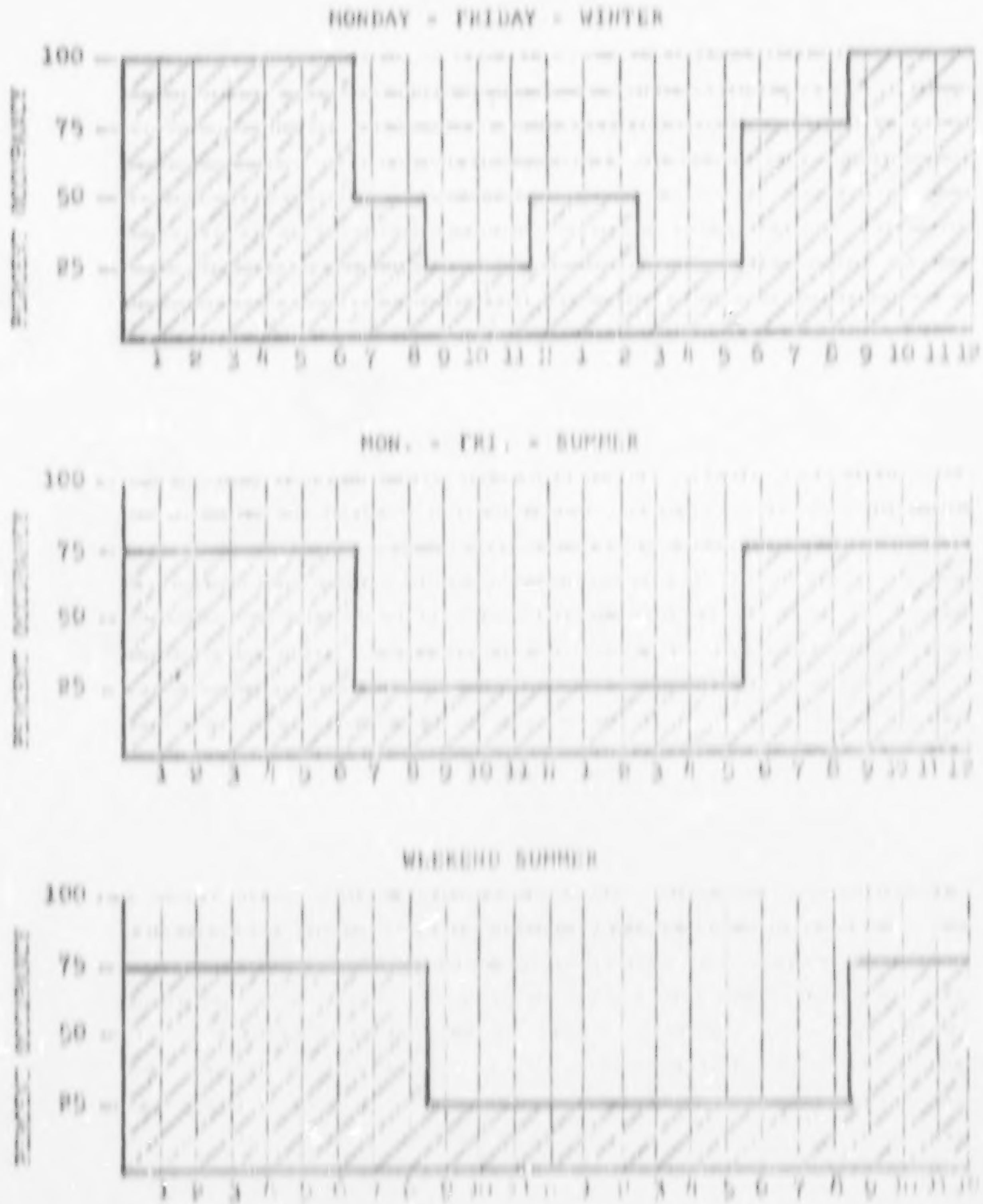

Figure 8: Apartment house. [155]

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best available copy.

WEEKEND - WINTER

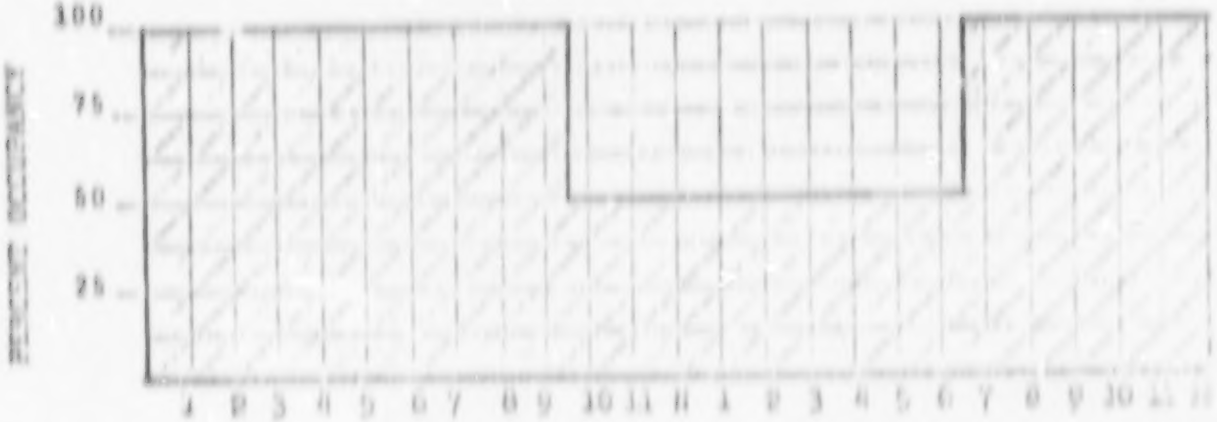
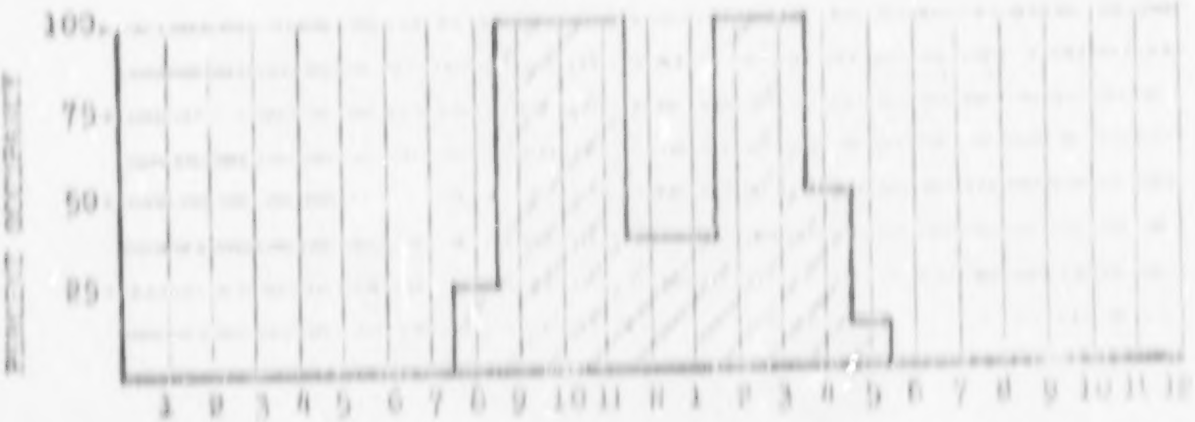


Figure 8: Apartment house [[illegible]] (concluded)

CLASSROOMS



WITH EVENING CLASSES

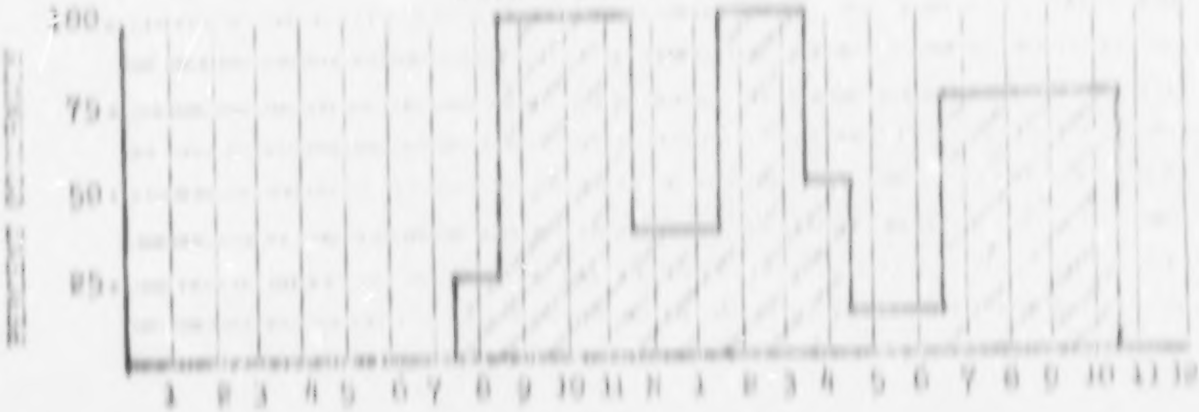


Figure 9: Elementary and high schools [[illegible]]

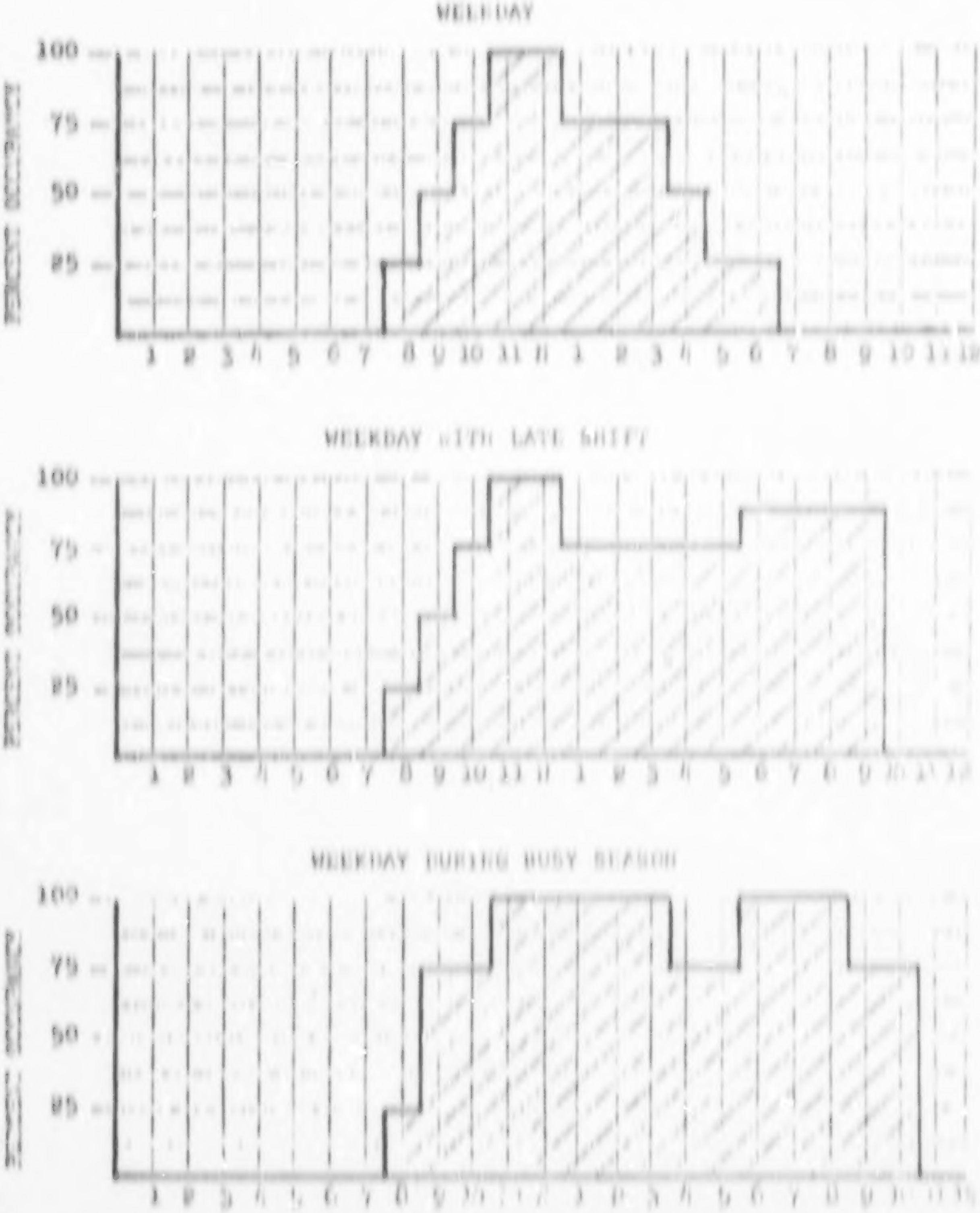
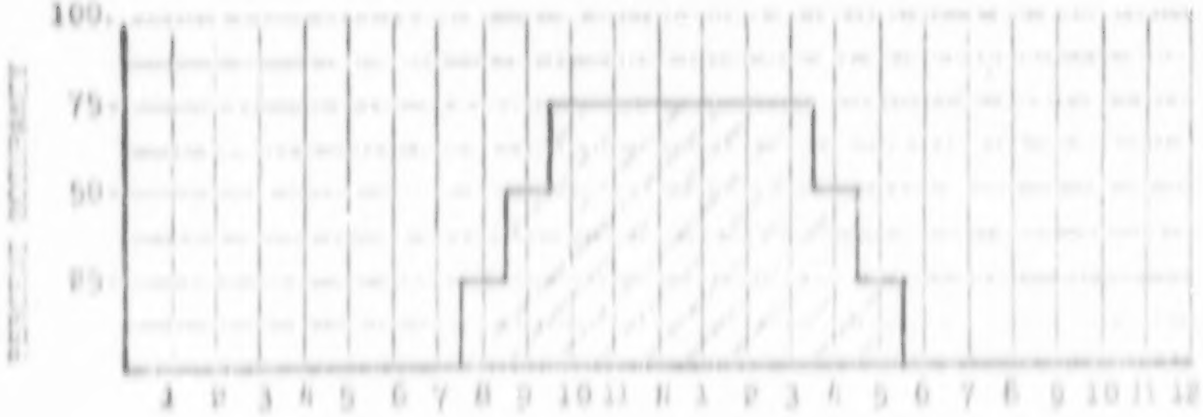


Figure 10. Shopping center. [[illegible]]

SATURDAY



SATURDAY IN BUSY SEASON

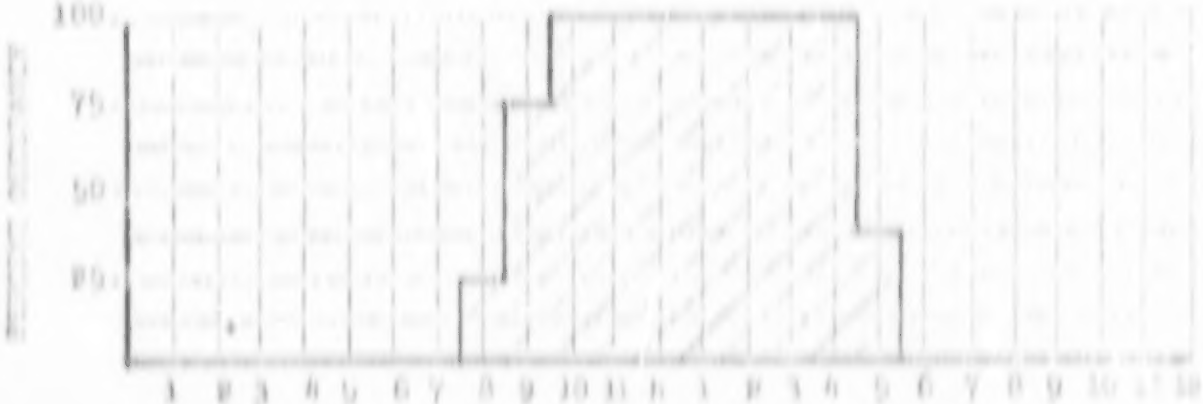


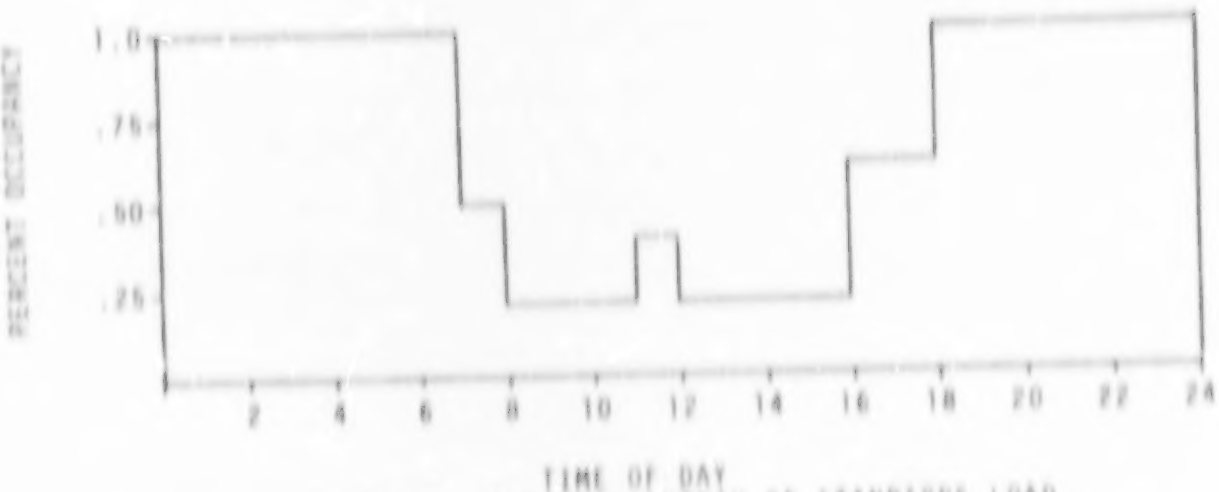
Figure 10. Shopping center [33] (Concluded).

Such estimates can be found in the literature for many building types. Reported here are the occupancy profiles for apartment houses, elementary and high schools and shopping centers, Figures 8, 9 and 10. These profiles show occupancy as a function of time of day for various building use modes relevant to the particular building type. For example, profiles for an apartment house are given for weekday and weekend, for summer and winter. The abcissa gives the hours of the day, while the ordinate measures the intensity of occupation, in terms of percent of the maximum occupancy for each particular building type.

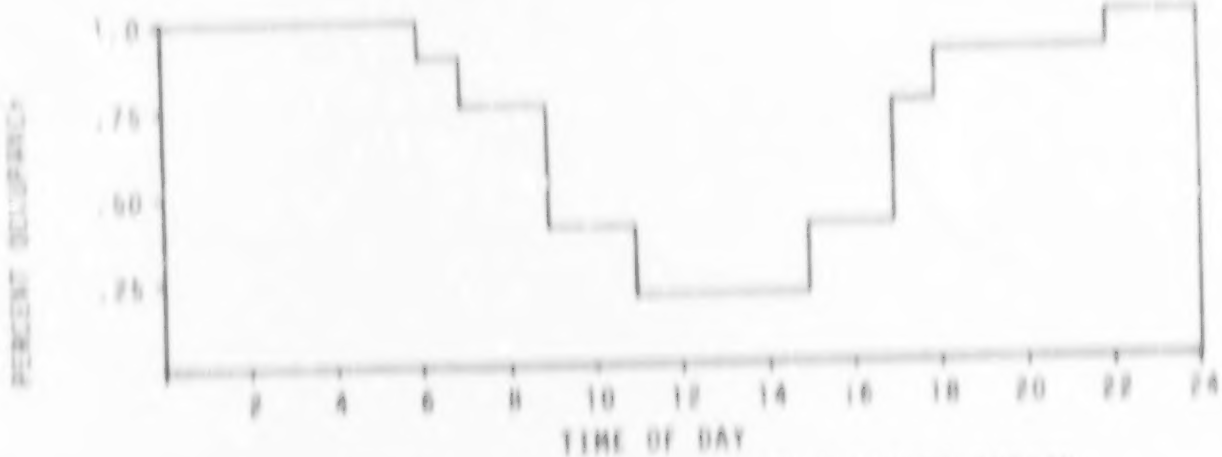
Occupancy profile information can also be obtained from computer models which use occupancy data to calculate building heating and cooling loads. Figure 11 shows the occupancy profiles for residential buildings used by two such programs. Both of these profiles show percent occupancy as a function of time of day.

In contacting design professionals, it was found that occupancy profiles are not often used in design work. The criteria which are normally used in designing buildings include: the use to which the building will be put (an office building will use different criteria than a supermarket); the maximum occupancy load of the building; how long, often and at what time the maximum occupancies will occur; as well as the ability to handle emergency situations (i.e., quick exits during fires) during peak occupancy periods.

Building heating, cooling, and ventilating systems will be designed to handle the peak occupancy levels and the specific temperature and ventilation problems which can arise at these times. For example,



SOURCE: NATIONAL BUREAU OF STANDARDS LOAD DETERMINATION PROGRAM



SOURCE: HITTMAN ASSOCIATES BUILDING ENERGY ANALYSIS MODEL

Figure 11. Computer model occupancy profiles - residence.

the cooling systems in a movie theater must be able to remove the body heat of a full house while a movie is being shown. In a movie theater, this occurs within well-defined time limits. In a residence, occupancy does not always follow as strict a schedule of occupancy, but the body heat of the people occupying a house at any point in time will usually not be an overwhelming factor in the design of the cooling system. A generalized occupancy profile, not specifying detailed time structure of occupancy but based instead upon daily averages, will suffice for HVAC system design.

6.2 HUMAN ACTIVITIES

The variety, frequency, and duration of human activities in indoor spaces is an important factor necessary to adequately determine indoor pollutant exposure. The occupancy profiles provide this for occupants in the aggregate, but for individual pollutant exposure studies it is usually necessary to collect this type of information through subject interrogation.

A study by Chapin [117] reports the distribution of human activities as a function of time. Results of this study are shown in Figures 12 and 13. In each of these two graphs, the percentage of persons engaged in a particular activity is shown as a function of time of day. The activities shown here, "sleeping," and "TV, rest and relaxation," are two which can easily be assigned to specific spaces within a residence. The information collected in this study, as in most studies of this kind, is in terms of types of activity, not in terms of locations of activity within the building. Therefore, some assumptions must be

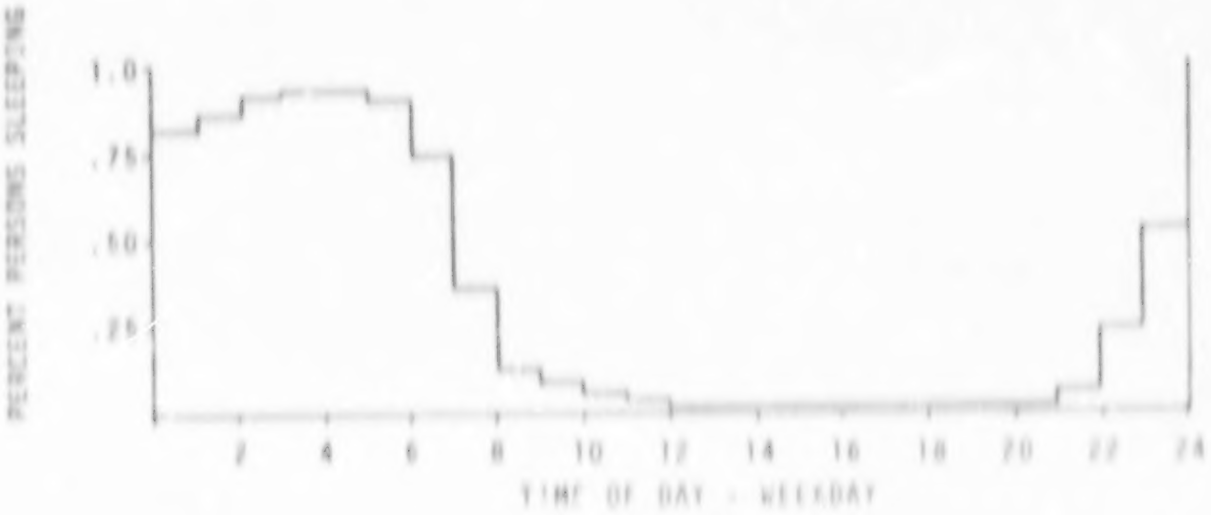


Figure 11. Profile of persons sleeping [100].

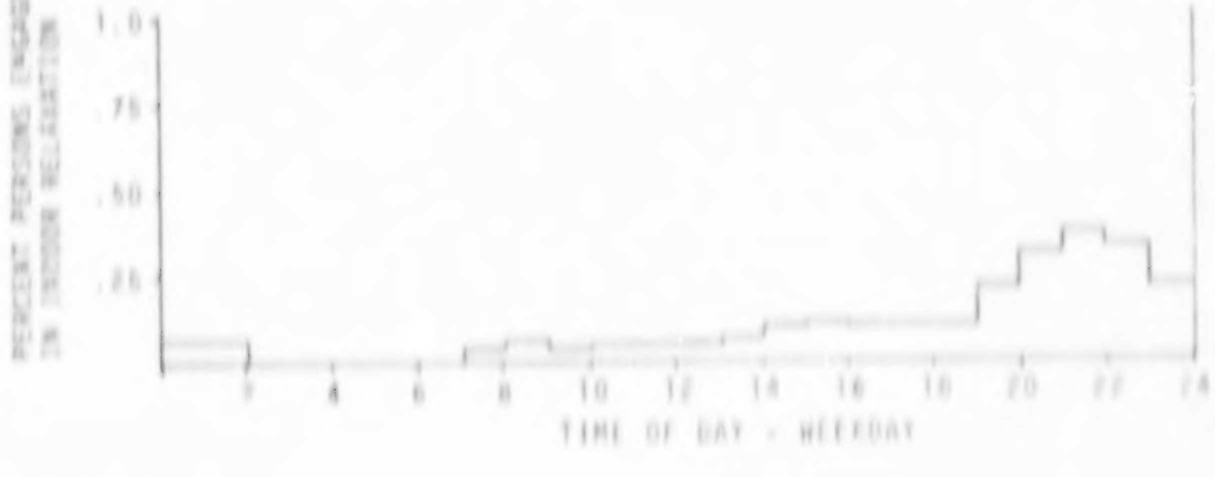


Figure 12. Profile of persons engaged in watching TV, [illegible], and relaxation [100].

made in order to find the time spent in various rooms of a house. For example, it is clear that the activity "sleeping" usually occurs in the bedroom. The activity "TV, rest, and relaxation" probably occurred in a living room or family room.

Cooking, an activity which probably has a large impact on indoor air quality, was not considered as a separate activity in Chapin's study. Hittman Associates [101] developed a profile showing percentages of maximum appliance load as a function of time of day. This appears in Figure 14. In this figure, a baseline of about 40 percent load represents appliances that are used continuously, such as refrigerators and freezers. The large peaks occurring in the morning, at noon, and in the evening are due almost entirely to cooking activity. Increased hot water use during these times also contributes to the peaks.

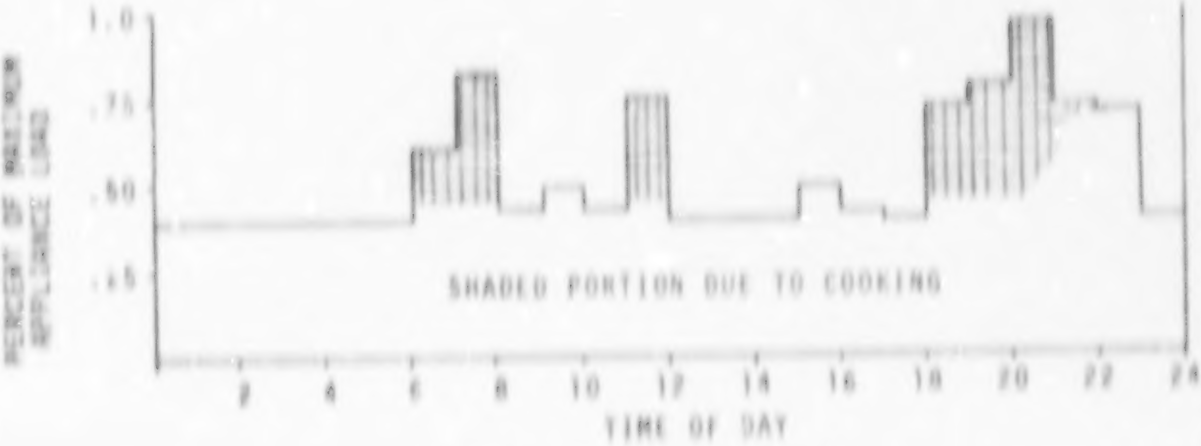


Figure 14. Appliance Use Profile [101].

One step in the investigation of human activity impact on indoor air quality is the setting of baselines of human occupancy hours during which indoor air must be suitably conditioned. This baseline involves making detailed estimates, for various types of spaces of the frequency, intensity, and duration of human occupancy which the spaces experience.

Chapin and Brail [118, 119] devised a 13-class activity profile of metropolitan activity and mobility patterns. These 13 person-initiated activities are delineated by the relative freedom with which a person engages in an activity. There are three categories in the system devised by these investigators. Firstly, activities are performed either in the home or outside the home allowing a basic split in environmental conditions surrounding activity performance. Secondly, the authors differentiate between discretionary and obligatory activities. Discretionary activities are those in which an individual exerts his own initiative towards the performance of the activity, such as reading, socializing, or relaxing. Obligatory activities are those sustaining activities required by human physiology, such as sleeping and eating. The terms discretionary and obligatory can be viewed as the "polar extremes," with most activities falling in between, having both discretionary and obligatory aspects. Finally, the 13-class activity profile differentiates activities by the level of interaction between the performer, other individuals, and their environment [118, 119].

Thus three parameters, location of activity performance, discretionary and obligatory classes, and levels of interaction, define elements of the following 13-class system:

1. Relaxation
2. Arts, hobbies, and sports
3. Reading
4. Television and radio
5. In-home family
6. In-home socializing
7. In-home obligatory
8. Out-of-home discretionary
9. Out-of-home family
10. Out-of-home socializing
11. Work related
12. Shopping and personal services
13. Out-of-home obligatory.

The first seven are in-home activities, and of these seven, the first six are classified as discretionary. In-home obligatory activities include housework; home, yard, or car maintenance; eating meals at home; personal care chores; child-centered activities; and the like. The last six activities are performed out-of-home, and the final three are obligatory. Out-of-home obligatory activities include household errands, medical care trips, taxi type driving chores, and eating meals out of the home within a nonsocializing context. As suggested earlier, the authors' focus has been upon the discretionary activities, and their activity classification scheme has been constructed with this focus in mind. Table 29 contains the percentages of individuals performing the different activities and the mean durations of those who do perform the activity at least once during the day [118].

TABLE 29. PERCENTAGES OF INDIVIDUALS PERFORMING AN ACTIVITY ONE TIME OR MORE DURING A WEEKDAY AND THE MEAN DURATIONS OF THE ACTIVITY, FOR METROPOLITAN UNITED STATES [118]

Activity Class	Percentage	Mean Duration (hours)
Relaxation	48	1.65
Arts, hobbies, and sports	10	2.76
Reading	29	1.34
Television and radio	66	3.09
In-home family	10	1.65
In-home socializing	14	1.81
In-home obligatory	100	5.67
Out-of-home discretionary	15	2.71[a]
Out-of-home family	11	2.33[a]
Out-of-home socializing	13	2.64
Work-related	47	8.69[a]
Shopping and personal services	35	1.72[a]
Out-of-home obligatory	49	1.57[a]

[a] Includes the full amount of travel time to the activity and from the activity if trip begins or ends in the home. If travel for the activity begins or ends in a place other than the home, only half the travel time for the leg of that trip is included in the time spent at the activity.

The personal activities of individuals may in themselves be pollutant-generating - as for example in the use of aerosol - as well as resulting in exposure by the individual to pollutants.

6.3 OVERVIEW

Building occupancy has been quantified for various structures as a percent of total occupancy by time. Information on occupancy of dwellings and rooms within dwellings and other structures has not been quantified, although such information can be obtained roughly from previous attempts at quantifying the amounts of time people use performing a variety of activities. Activity profiles of building occupants have been investigated, although these are of only moderate use in relation to activities involving building ventilation or indoor pollutant generation. It is evident that, if data about human occupancy of indoor space are to be used in future to determine human exposure to indoor pollutant concentrations and pollutant dosages, it will be necessary to obtain data based on a more finely structured grid of space and time dimensions within buildings than has been customary in the occupancy research described in this report.

Section 7.0

ENERGY CONSERVATION MEASURES IN BUILDINGS

7.1 INTRODUCTION

This section has two purposes. The first is to provide an appraisal - based upon a review of relevant literature - of the state-of-the-art technologies available for reduction of energy use in buildings. The second purpose is to consider - again based upon the literature - some of the relationships between energy conservation measures and indoor air quality characteristics of buildings.

In Section 7.2, there is a discussion of various possible energy conservation modifications categorized into those which do and those which do not directly affect air change rates in buildings. Where possible, an attempt has been made to quantify the perturbation of air change rate of a particular modification.

Subsequently in Section 7.3, there is a discussion of building climatology and of some of the relationships between indoor air quality and the operations of heating, ventilating and air conditioning systems in buildings. A detailed investigation and evaluation of the effectiveness of commercially available air cleaning devices (for example, filters and electronic precipitators), and of quantitative relationships between energy conservation measures and indoor air quality, was not included in the scope of the first phase assignment which resulted in this present document. A detailed study of that kind, intended to produce quantitative information about air cleaning-air quality-energy conservation-cost relationships in indoor environments, based upon a combination of literature search and new field research, will soon begin as a part of the Phase II EPA-sponsored study of indoor air pollution being performed by GEOMET. Results of that study will become available in late 1977. The discussions of indoor air quality and energy conservation relationships which appear in Section 7.3 of the present document are therefore of a preliminary, qualitative nature only.

7.2 ENERGY CONSERVATION MODIFICATIONS

7.2.1 Definition of Characteristic House

Many examples will be given in this section that require examining a specific residential building. In order to facilitate this, a characteristic house has been defined. This house is representative of many residential buildings in the northeastern part of the United States. It should be noted that an attempt was made to use a somewhat "average" characteristic house, but that it could not possibly be representative of all styles of houses in the U.S. Specific results and conclusions based on an analysis of the characteristic house are not necessarily directly applicable to other style houses.

The structural and energy consumption parameters which describe the characteristic house are given in Table 30; the floor plan of the house is shown in Figure 15.

7.2.2 Structural Modifications

The first group of energy conservation measures which will be discussed is structural modifications to a building. Some of these modifications can practicably be considered only in the design stage of

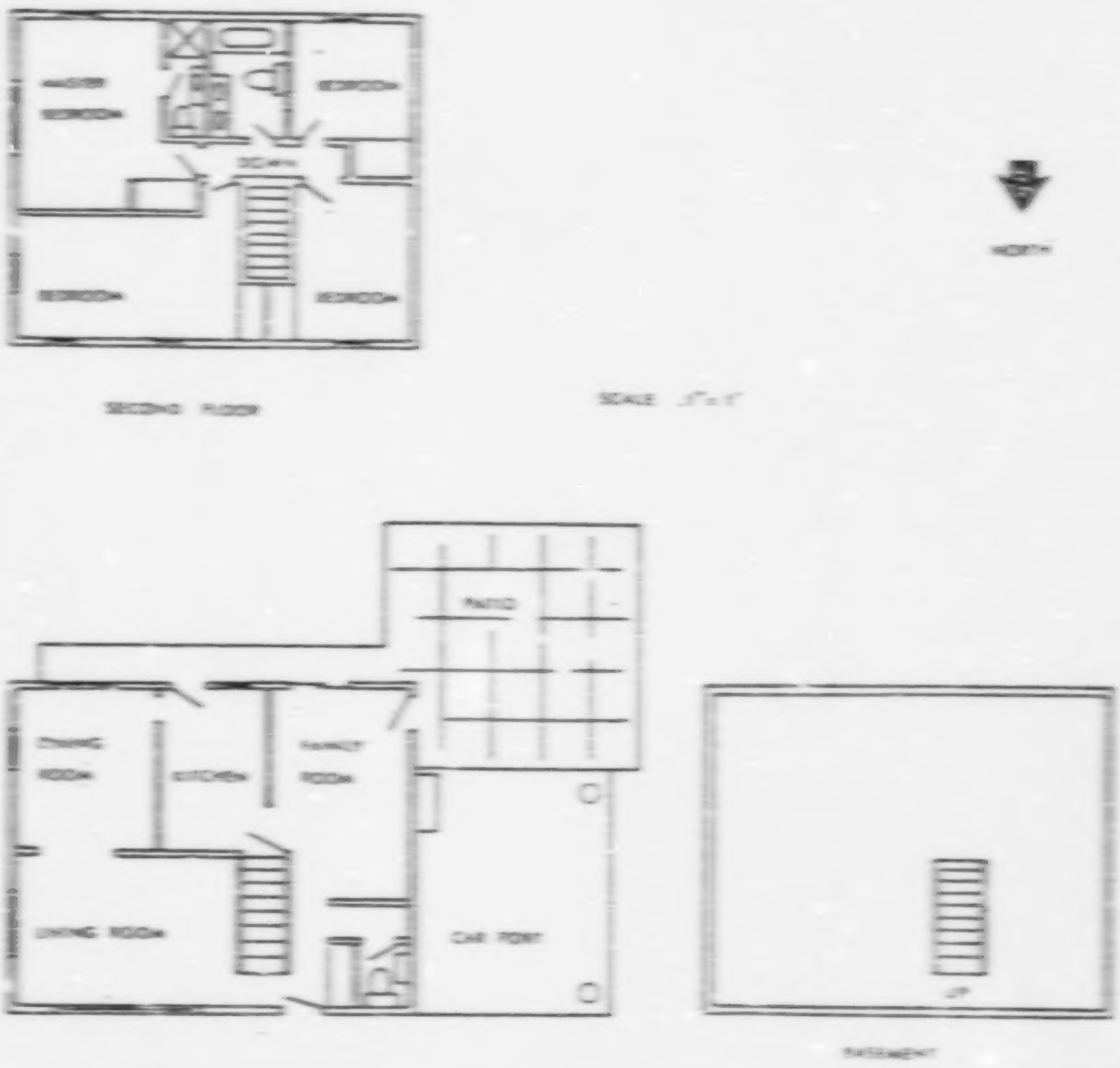


Figure 15. Floor plan of characteristic house.

TABLE 31. DESIGN PARAMETERS FOR CHARACTERISTIC HOUSE

Structure Parameters	
Number of Stories	Two
Basement	Full (Unfinished)
Garage	Attached, Open Carport
Floor Area, ft^2	1895 Finished
Construction Type	Wood Frame
Exterior Walls	
Outside Surface	Wood Shiplap
Sheathing	Plywood, 1/2 inch
Insulation	R-7 Batting, 1/2 inch
Inside Surface	Drywall, 1/2 inch
Ceiling Insulation	Loose Fill Blown-in 5 inches
Attic	Ventilated, Unheated
Roof	Asphalt Shingles
Windows	
Type	Aluminum Casement
Glazing	Single
Area	180
Exterior Doors	
Type	Wood Panel
Number	3
Total Area, ft^2	60
Patio Door	
Type	Aluminum Frame
Glazing	Single
Area, ft^2	40

R7 Equivalent to 2-1/4 inch Fiberglass Batting.

Energy Consumption Parameters	
Energy Consuming Equipment:	
Heating System	Forced Air, Gas
Cooling System	Forced Air, Electric
Hot Water Heater	Gas
Cooking Range	Gas (90 therms/year)*
Clothes Dryer	Gas
Refrigerator/Freezer	Electric (1430 kw-hr/year)*
Lights	Electric (2000 kw-hr/year)*
Color TV	Electric (500 kw-hr/year)*
Furnace Fan	Electric (394 kw-hr/year)*
Dishwasher	Electric (363 kw-hr/year)*
Clothes Washer	Electric (103 kw-hr/year)*
Iron	Electric (144 kw-hr/year)*
Coffee Maker	Electric (106 kw-hr/year)*
Miscellaneous	Electric (1200 kw-hr/year)*

* Energy Input to Structure Due to Use of Item.

Factors Affecting Heating/Cooling Load: (Base Case)	
Exterior Glass Areas	70% Draped 20% Shaded 10% Open Patio Door on South Wall No Awnings, No Storm Windows
External Landscaping	No Shading Effect
Dwelling Facing	North
External Colors	White Roof and Walls
People	Two Adults, Two Children
Weather	Data for 1954 from Baltimore, MD. Weather Station
Garage Location	West Side

a building (such as building orientation, ratio of external wall area/floor area, and thermal capacity of the structure). Most of the other modifications can be considered either before or after the building has been erected. The first part of this section will be devoted to those structural modifications which have, as their primary effect, an impact on air infiltration into a building. The second part of this section will deal with structural modifications which do not directly affect air infiltration, but conserve energy in some other way.

7.2.2.1 Modifications Which Directly Affect the Air Change Rate

Storm Doors and Windows

Storm windows have been cited by the National Bureau of Standards as the one insulating component that saves more fuel dollars than any other component. (This result is based on a test house in which the NBS engineers monitored different energy saving measures using infrared photography.) The fuel savings achieved by the addition of storm windows over typical single-glazed windows are through two mechanisms:

- They reduce infiltration of outdoor air through the window area by increasing the resistance to air flow through the cracks between the window sash and frame.
- They create a relatively inactive air space between the primary window and the storm window, which adds insulating value to the window area.

The addition of storm windows will typically reduce infiltration around the window due to wind by about 15 to 30 percent. They will also reduce the conductive heat loss through the glass area by about 50 percent. The combined effects of reduced infiltration and increased insulation resulting from the addition of storm windows can represent a total savings on fuel for heating and cooling of 10 to 25 percent in typical residential buildings. The exact savings achieved by any particular installation will depend on the characteristics of the building, the quality and type of the materials and the workmanship.

The types of storm windows which may be installed vary widely, from a plastic sheet taped over the window to a permanently installed system which allows for opening of the storm sash and sliding a screen into place over the opening. In any type of storm window, the benefit gained from it will be affected by the quality of the product and the workmanship of the installation. If large cracks are left around the perimeter, the window will be less effective in reducing infiltration.

Storm doors affect infiltration in the same way as storm windows; that is, they increase resistance to air flow through the cracks around the door. Storm doors, however, do not reduce the conductive losses through the door area as effectively as storm windows reduce the conductive loss through the window area. Table 31 shows the difference in conductive loss per square foot of area for windows with and without storm windows, and for doors, with and without storm doors. Table 31 shows a reduction for conductive losses through the window area of 47 percent due to the addition of storm windows, and a reduction of conductive losses through the door area of 36 percent due to the addition of storm doors. The reason that the reduction of conductive losses due to storm doors is less than for storm windows is that a door is usually a better insulator than a window. The addition of a small amount of insulation to a door therefore has less of an effect than the addition of a small amount of insulation to a window [2, 18, 38, 145, 157, 327, 254, 174, 299, 302, 340, 449, 596, 300, 301, 51, 477, 667, 668].

TABLE 31. INSULATING EFFECTS DUE TO THE ADDITION OF STORM DOORS AND STORM WINDOWS

	R-Value	U-Value (Btu/Hr.Ft.^{2} °F)	Percent Reduction of Heat Flow
Door Only	1.77	0.565	
Door and Storm Door	2.77	0.361	36%
Window Only	0.94	1.06	
Window and Storm Window	1.79	0.56	47%

Caulking and Weatherstripping

Air infiltrates into a building through any opening or crack, such as those around window and door frames, whenever the pressure outside is greater than the pressure inside. The amount of infiltration is a function of the pressure difference and the size of the crack or opening. Therefore, filling cracks with caulking and installing weatherstripping to reduce the crack size around windows and doors will decrease infiltration.

Tests have shown that the use of properly installed weatherstripping can reduce the infiltration through the cracks between window sash and frame by as much as 80 percent. To achieve results like this, the weatherstripping must be reasonably good quality material, it must be cut accurately to the size of the window, and it must be carefully installed to insure that no gaps are left when the window is closed.

Caulking any cracks will also reduce air infiltration. The most common places cracks occur which should be caulked are:

- Around window and door frames
- At corners formed by siding
- At the foundation sill
- Where pipes or wires penetrate the outside wall or a wall or floor between a heated and unheated space
- Where two different materials meet (such as masonry meeting siding)
- Where the ventilators, mail slots, or other penetrations of the exterior wall occur.

References are [2, 18, 44, 157, 174, 201, 327, 254, 287, 299, 300, 302, 340, 398, 449, 596, 597, 477, 667, 668].

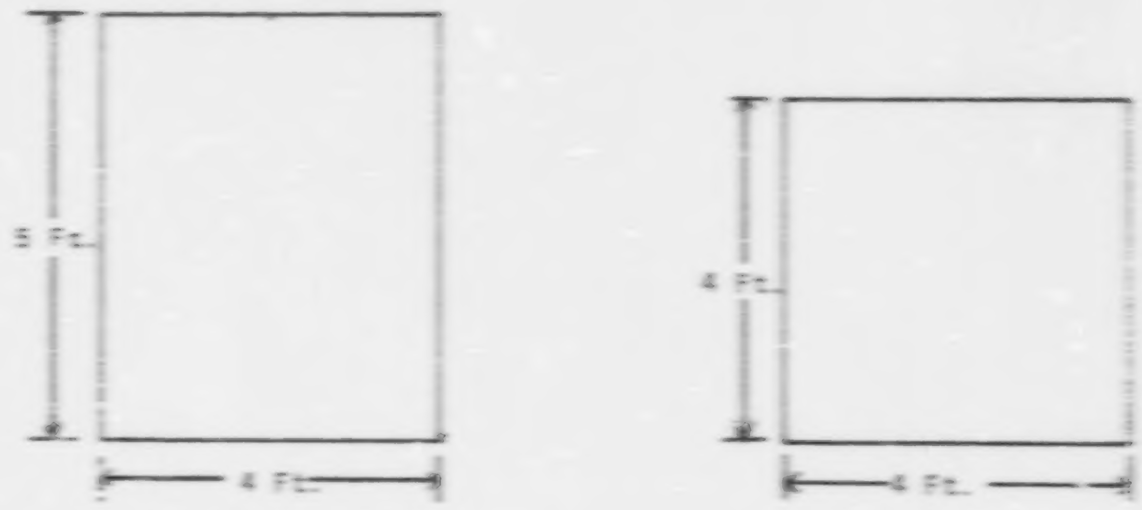
Pointing and Filling

As a brick or stone building ages, the mortar joints deteriorate and begin to crumble. The weight of the masonry itself is usually sufficient to prevent large gaps from forming in the walls, but smaller gaps may still be formed. Pointing and filling reduces the size of the cracks and crevices in a masonry wall, thus reducing the infiltration through the wall [302].

Decreased Window Area

Air infiltrates into a building through the cracks around the outside of any window. A reduction in window area would produce a reduction in the total crack length around windows. However, the crack length is not reduced by as large a percentage as the window area. Since area is a function of the square of linear dimensions, a reduction in window area produces a reduction in crack length approximately equal to the square root of the reduction in window area. For example, a 4' x 5' window has 20 ft^2 of area and 18 ft of crack around the perimeter. The area of the window would be reduced to 80 percent of 20 ft^2 or 16 ft^2 if it were changed to a 4' x 4' window. But a 4' x 4' window has 16 ft of crack, about 89 percent of 18 ft or ($\sqrt{0.8}$) x (18) (see Figure 16). This relation is very close for windows that are approximately square, but breaks down on windows that are very long and narrow.

Besides reduced infiltration due to fewer linear feet of crack around a smaller window, such a modification is also accompanied by an increase in the overall insulating value of gross wall area. Since solid walls are typically better insulators than windows by nearly an order of magnitude, any decrease in window area, and replacement of that area by solid wall, would bring about a net increase in the insulating value of the gross wall area [18, 44, 201, 239, 299, 300, 302, 340, 363, 596, 477, 498].



	Window A	Window B
AREA	20 Sq. Ft	16 Sq. Ft
PERIMETER	18 Ft	16 Ft

AREA OF B $=$ (0.8)(Area of A)

PERIMETER OF B $\approx$ ($\sqrt{0.8}$)(Perimeter of A)

Figure 16. Window perimeter crack length as a function of area.

Building Orientation and Configuration

The orientation of a building with respect to its environment can have a large impact on the amount of energy required to maintain comfortable conditions inside the building. The two factors in the natural environment whose impact is affected most by building orientation are sun and wind. Conditions usually dictate that the ideal orientations with respect to each of these two factors are different. A detailed analysis is required for any particular building to determine the optimum orientation. The optimum orientation is normally a compromise among the ideal orientations with respect to each factor considered. The magnitude of the impact of each factor must be examined and tradeoffs made in order to arrive at an overall ideal orientation.

Orientation with Respect to Sun

The sun affects buildings and their energy use in many ways. It shines through windows providing light and warmth for the building's occupants. In the winter months, the heat gained from the sun is welcome, but in the summer, the additional heat from the sun must be removed by the building's air conditioning system.

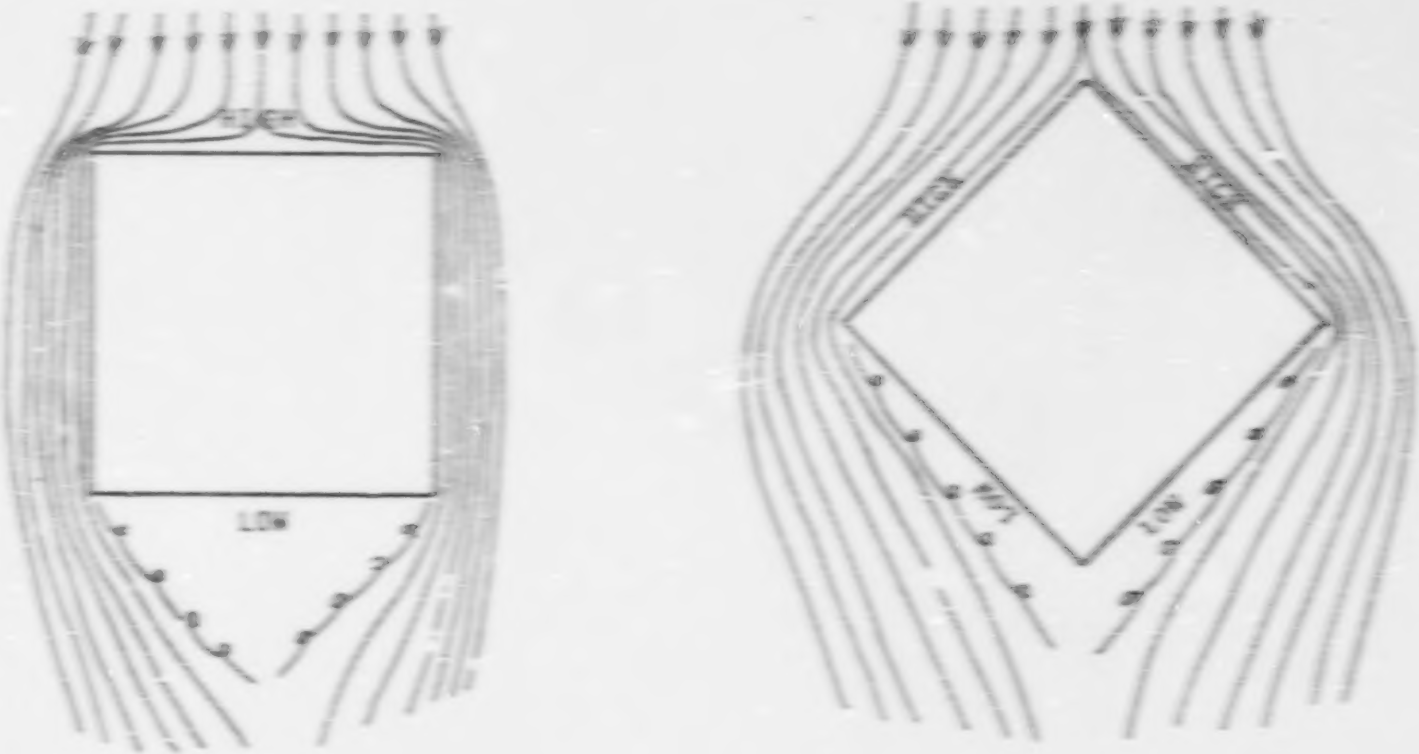
The amount of sunlight which shines in through a window or impinges on an opaque surface depends upon its orientation. The ideal orientation with respect to the sun for any particular building is a unique problem and depends upon the geographic location, building physical parameters, building use, etc. Generally (in the Northern Hemisphere) buildings in warm climates should have a minimum of glass on the southern side; buildings in cold climates should have a minimum of glass on the northern side. The longer dimension of a building should lie in a generally east-west orientation to avoid unnecessarily wide variations of solar impact on the building during the day.

Orientation with Respect to Wind

The impact of building orientation on winds effects are shown Figures 17 and 18. Figure 17 is typical of most single-family houses; Figure 18 is typical of townhouses or low-rise apartment buildings.

As shown in Figure 17, the rotation of a building that has approximately the same dimensions on each of its four sides by 45° radically changes the air flow pattern around the building. In Figure 17a the direction of the wind is normal to one of the surfaces of the building, creating a very high pressure zone on the windward side of the building. The resultant effect on the building is infiltration of air through the wall on the high pressure side and exfiltration of air through the wall on the leeward side. In Figure 17b, no surface of the building is normal to the direction of the wind. The resultant flow of air around the building is substantially less turbulent and with smaller pressure differences than in Figure 17a. Because of the smaller pressure differences, air infiltration is considerably less in Figure 17b than in Figure 17a. (If windows are fairly evenly distributed on all four walls, Figure 17b would have about 15 percent less infiltration due to wind than Figure 17a.)

Figure 18 shows the importance of orientation with respect to prevailing winds of a building which has one dimension much larger than the other, such as is typical of townhouse or low-rise apartment construction.



17a.

17b.

Figure 17. Air flow around single-family dwelling, as a function of orientation with respect to wind direction.

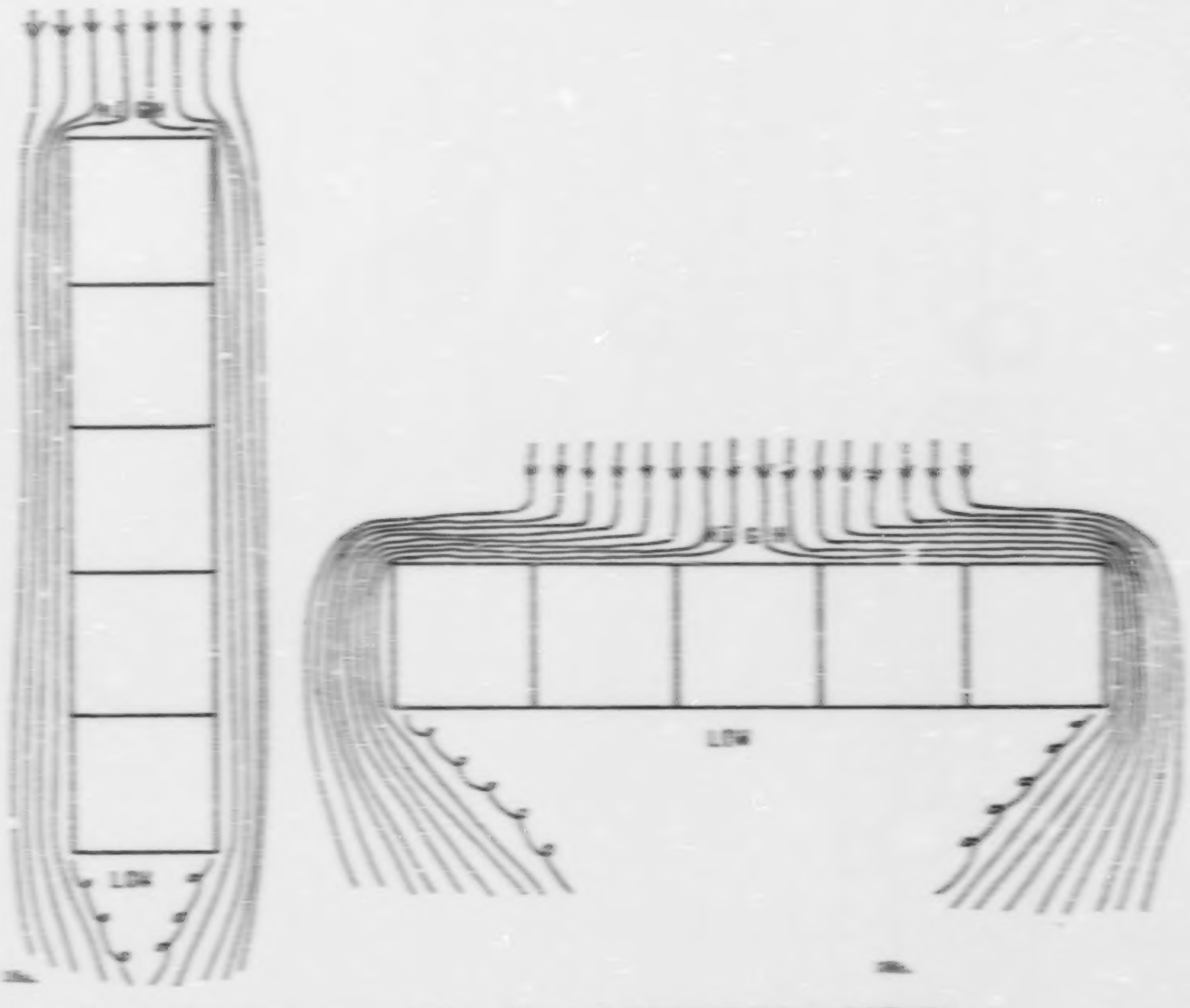


Figure 35. Air flow around townhouse or low-rise apartment building as a function of orientation with respect to wind direction.

In Figure 18a, the building is situated to minimize air infiltration due to wind. The high pressure zone created at one end of the building and the low pressure zone at the opposite end cause infiltration in the two end units. But since a path through the building in the long dimension is blocked by several party walls, infiltration effects in the interior apartments are minimized. If the building is oriented as shown in Figure 18b, a high pressure zone is created all the way across one long dimension of the building, and a low pressure zone on the outer side. This causes increased infiltration in all the units in the building [18, 157, 239, 299, 300, 302, 340, 363, 474, 596, 668, 719].

Non-Operable Windows

The infiltration of air through the spaces between an operable window sash and the frame accounts for about 50 percent of the infiltration due to wind in the average residence. The infiltration through cracks around the window frame account for an additional 15 percent. If an operable window were replaced by a non-operable window, the crack size around the window would be greatly reduced, though not completely eliminated. This would reduce the infiltration due to the window but would not affect the infiltration due to the window frame.

This particular modification would also eliminate the possibility of using natural ventilation. Mechanical ventilation would be required year-round. In residential applications, such a modification would have to be considered as having an impact on the life style of the occupants of the residence. In addition, the need for year-round mechanical ventilation would offset some of the energy savings due to reduced infiltration [302].

Elimination of Fireplace

A fireplace can add to the esthetic value of a room, and when it is in use, it supplies that room with a considerable amount of heat. But while a fire is burning, a considerable quantity of air is being drawn into the house through all the cracks around doors, windows, etc., and drawn up the chimney. In fact, depending on the size and stage of the fire, a fireplace can cause over 200 cfm of infiltration, which would approximately double the infiltration in an average house. This causes all the rooms other than the one in which the fireplace is located to become quite cool unless one provides for ventilation air directly to the fireplace. (Opening a window in the room to provide air for the fireplace is a possible solution, though this causes cold drafts within the room.)

During the course of a typical use of a fireplace in a residence, including burning of the fire, and allowing for the damper to remain open until the following morning, it is estimated that approximately 85,000 ft^3 of outside air are drawn through the house, or a total of approximately 6-1/2 air changes in an average size (1600 ft^2) house. Assuming a 50° F temperature difference between indoor and outdoor, approximately 1/2 gallon of oil would be required to heat the air which infiltrated due directly to the fireplace.

Even when not in use, unless it is provided with an unusually well-fitted damper, a fireplace is responsible for some infiltration. Assuming a crack around three sides of the damper of about 1/4 inch, one could expect an infiltration rate of about 20 to 25 cfm through the chimney [299, 302, 340, 499, 596].

Recirculating Kitchen Hood

A kitchen exhaust fan handles an average daily flow of about 14,000 cubic feet of air. This is based on an 80 cfm fan operating about three hours per day and accounts for one complete air change in a 1600 square foot house. If this air is all exhausted to the outside, it is causing an equal volume of air to be drawn in from the outside through the cracks around windows, doors, etc. The modification of a kitchen hood to a recirculating fan instead of an exhaust fan would eliminate this flow of air into the house. Let us look more carefully at the implications of the modification.

In operation during the heating season, an exhaust fan would be discarding useful heat (the temperature of the exhaust air would be about 110°F) and drawing in cold air from the outside, imposing an additional load on the heating system. A recirculating fan would put the heat and moisture from cooking right back into the house where it assists the heating system in maintaining comfortable conditions. But during the cooling season, a recirculating fan would do nothing to remove the heat and moisture generated in cooking. Instead, the entire load generated by the stove would have to be removed from the house by the cooling system. An exhaust fan, however, would remove much of the heat and moisture generated in cooking, and even though it would cause additional infiltration of air, the outside air being drawn into the house would almost always be cooler that the exhaust air.

Since it is impractical to install two kitchen fans, one that recirculates air and one that exhausts the air to the outside, it is important to choose the right type of fan for a particular installation. In general, a recirculating fan would be better in cooler climates, and an exhaust fan would be desirable in warmer climates [254, 299, 302, 340, 667].

Vestibule Doors

The use of vestibule doors in place of single doors affects energy consumption for heating and cooling in three ways:

1. They reduce air infiltration into the building by increasing the resistance of air flow through the cracks around the door.
2. They increase the insulation value of the door area by the addition of an air space (the vestibule).
3. They decrease the quantity of outdoor air entering the building each time the door is used as an entrance or exit.

By creating a buffer zone between the interior of the building and its external environment, the use of vestibule doors is more effective in saving energy than storm doors. The savings achieved by using vestibule doors instead of single doors are twice as large as the savings achieved by using storm doors [18, 38, 299, 302, 448].

Automatic Door Closers

Each time a door is opened to allow a person to enter or leave a building, outside air enters the building, displacing the air that was previously occupying the space. The volume of air that enters a building each time a door is opened depends upon the wind speed, the duration for which the door is open, and any air pressure differences between the interior and exterior of the building. By reducing the time a door is open, an automatic door closer decreases the volume of outside air which enters the building [18, 327, 299].

Outdoor Landscaping

The proper use of trees as windbreaks can reduce air infiltration into a building. A windbreak temporarily diverts a fraction of the airstream upward, creating an area on the leeward side of the windbreak that has reduced wind speeds. The airstream will return to the level from which it was diverted, but typically a 50 percent reduction in wind speed will be experienced as much as 15 barrier heights downwind of the windbreak. For example, if the barrier were 20 feet high the 50 percent reduction in wind speed would be present, at most, 300 feet downwind of the barrier. Since trees let some wind through it is unusual for a windbreak constructed of trees to cause a reduction of as much as 75 percent in wind speed, but a large area downwind of the trees will experience a modest reduction in wind speed. A distance downwind of the windbreak equivalent to almost 30 times the height of the windbreak may experience more than a 25 percent reduction in wind speed.

Barriers which allow little or no wind to penetrate at the lower levels provide a short range of very good wind protection (over 75 percent reduction in wind speed), but not as extended a range of moderate protection as provided by a less dense barrier. Also within the area of 75 percent reduction of wind speed, eddies and turbulence can be expected [18, 167, 474, 596].

7.2.2.2 Structural Modifications Which Do Not Directly Affect Air Change Rate

Insulation of Walls, Roof, and Floors

Insulation is a material that has a high resistence to the flow of heat. The use of these materials in insulating the walls, roof, and floor of a building is the most basic energy conservation measure that can be taken. It is cited as one of the first steps to take in almost every reference that deals with ways to save energy in buildings. The installation of an average thickness of insulation or the deletion of insulation entirely from the walls, roof, and floor of a house can cause a variation in the energy required for heating and cooling of about 50 percent.

The resistivity of a material to the flow of heat is termed the R-value of that material. The reciprocal of the R-value is the U-value, which is a measure of the conductivity of a material. Each of the many materials used for insulation (e.g., wood, wood fiber products, plastics, brick, glass fibers and plaster board) come in different forms, such as boards, foams, blankets, loose particles and masonry. The R-value will be specific for the material and the form (boards, blankets, etc.) that it is in. The resistence to the flow of heat by any given material and form is determined by multiplying the resistivity (R) by the thickness of the material.*

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* Merkel, J.A. 1971. Basic Engineering Principles. University of Maryland, College Park, Maryland.

In the characteristic house defined at the beginning of this section, the part of the heating load due to losses through the walls, roof, and floor is about 30 percent of the total heating load. The walls, roof, and floor also account for about 20 percent of the cooling load. If the insulation were removed from the roof and walls, the R-values of those components would change as shown in Table 32.

TABLE 32. COMPARISON OF VALUES WITH AND WITHOUT INSULATION

	R-Value		U-Value	
	With Insulation	Without Insulation	With Insulation	Without Insulation
Wall	10	3	0.1	0.33
Roof	15	4	0.067	0.25

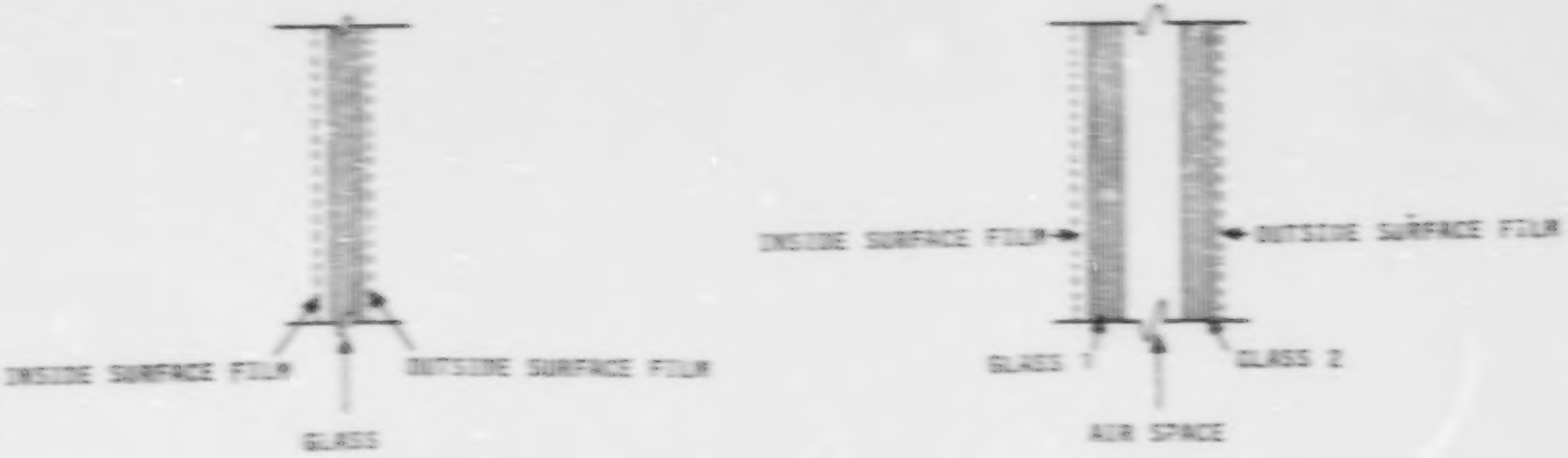
As Table 32 shows, the heat flow through either the walls or the roof would increase more than three times if the insulation were removed from the house. The increased heat flow through the walls and roof would result in an increase of about 50 percent for the energy needed to heat and cool the house.

Perhaps as important as the insulation itself is the manner in which it is installed. If insulation is cut short so that it does not extend the full width, height, or length of the space it was intended to fill, then heat leaks out around the edges of the insulation. Care must be taken when installing insulation in attic floors so that ventilation of the attic is not blocked. (Ventilation is required to remove moisture which would otherwise condense in the insulating material, lowering its R-value.) Small spaces around windows and doors must be filled with insulation or heat will leak out through those spaces. Vapor barriers must be installed properly or moisture will condense in the insulation and lower its efficiency. When insulation is compressed more than it should be, as is usually done to fit it around pipes, it loses efficiency. Installing insulation properly is not difficult, but it can greatly improve the performance of any insulating material [2, 18, 44, 70, 145, 157, 327, 201, 230, 254, 174, 287, 299, 301, 302, 340, 363, 448, 449, 453, 474, 499, 518, 596, 598, 666, 668, 667, 719, 51, 477, 498].

Double-Glazed Windows

While windows typically comprise 5 to 8 percent of the total area of the envelope of a residential building, they account for nearly 30 percent of the conductive losses through the building envelope. A double-glazed window can reduce the conductive losses through the glass area by about 50 percent.

Figure 19 shows the components through which heat must flow for a single- and double-glazed window. Figure 19a shows that for single-glazed windows, almost all of the thermal resistance is in the air films on the interior and exterior surfaces of the glass. The double-glazing (Figure 19b) retains the benefit of the interior and exterior surface air films, and adds a very significant air space. The extra thickness of glass has very little effect on the increased R-value of a double-glazed window. Window manufacturers have achieved U-values even lower than 0.58 by utilizing special surface treatments on the glass surfaces which face the air space [18, 44, 327, 201, 174, 301, 302, 340, 363, 448, 449, 668, 667].



A. SINGLE GLAZING

	R-Value
Inside Film	0.67
Glass	0.04
Outside Film	0.17
Total	0.88

$$U = \frac{1}{R} = \frac{1}{0.88} = 1.13$$

B. DOUBLE GLAZING

	R-Value
Inside Film	0.67
Glass 1	0.04
Air Space	0.8
Glass 2	0.04
Outside Film	0.17
Total	1.72

$$U = \frac{1}{R} = \frac{1}{1.72} = 0.58$$

Figure [illegible]. Window components which contribute to the resistance to heat flow.

Operable Insulating Shutters

The heat loss or gain through glass areas can be reduced by 80 to 90 percent (Table 33) when an insulating shutter is in place over the window. Since the conductive losses through the glass area of residential buildings typically comprise about 30 percent of the building's conductive losses, insulating shutters would reduce the conductive loss for the entire building by about 25 percent while the shutters are closed.

TABLE 33. BENEFITS OF INSULATING SHUTTER

R-Value		U-Value	U-Value
Window	0.88	With Shutter =	Without Shutter =
Insulation	5		
Total	5.88	$\frac{1}{5.88} = 0.17$	$\frac{1}{0.88} = 1.13$
$\frac{1.13 - 0.17}{1.13} = 0.85$ = 85% Reduction in Heat Loss/Gain			

Of course, the installation of insulating shutters in a building does not guarantee an energy saving. The occupants of the building must be willing to use the shutters, which means that the shutters must be designed so that they are attractive and easy to use [290, 596, 668, 667].

Increased Thermal Capacity of the Building's Structure

If two buildings were identical except for their thermal capacity, the building with the larger capacity would use less energy. This effect is most pronounced if the additional thermal capacity is in the envelope of the building. The greatest impact of this effect is on the cooling load.

When the sun shines on a building wall, it heats the wall. If the wall has a very small thermal capacity, that heat is seen as a load on the inside of the building in a very short time. If the wall has a greater thermal capacity, it can take several hours before the sun's heat is transferred through the wall to the interior. When the load finally reaches the building's interior, the peaks have been reduced and distributed over a longer period of time. This allows for smaller size air conditioning equipment. Besides distributing peak loads over a longer period of time, a wall with a large thermal capacity may hold the sun's heat well into the evening. When the temperature outside begins to drop, some of the heat in the wall will flow back out and never appear as a load on the air conditioning system. Also, by delaying the time that the load from the sun is felt inside the building, some of the heat will be removed by the air conditioning system in the evening, when cooler outdoor temperatures allow higher cooling efficiency [18, 239, 299, 448, 474].

Provide Shading for Windows

In an ideal situation, sunlight would be admitted into a building through the windows at times when the outdoor temperature is low, and prevented from entering the building when outdoor temperatures are high. One action in achieving this ideal situation is the proper orientation of the building, discussed earlier in this section. Another action is to provide proper shading of a building to control the admission of sunlight through the windows. Sunlight control can be provided in three ways:

1. Reduce the transmission of sunlight through the glass.
2. Prevent the sunlight from reaching the window through the use of shading devices.
3. Use shading devices inside the window.

Reduce Transmission Coefficient of Glass

This modification to a building is not really selective control of sunlight; it effects a reduction of sunlight admitted into the building at all times. While this solution may not be applicable to many locations in the U.S., in warm climates, where cooling is required most of the year, this is a reasonable solution.

Prevent Sunlight from Reaching the Window

When executed properly, this modification is the most effective method of controlling sunlight. The two most widely used methods of preventing sunlight from reaching the window are projections of the building structure, including roof overhangs and awnings, and planting of trees.

Building projections can be designed to allow sunlight to reach windows in the winter months, but shade the window during the summer months. This is due to the fact that the sun is higher in the sky during the summer than during the winter. By examining the solar angles in any specific location, it is possible to determine the dimensions a building projection would have to be to selectively block the sunlight.

Trees can also provide an effective control of sun. The planting of deciduous trees near a building would achieve the desired result of selective admission of sunlight. During the warm seasons, the trees provide a very effective shading device. In the winter months, once the leaves have been lost, deciduous trees allow most of the sunlight to pass through, between their branches, and into the building through its windows.

The most significant drawback to either building projections or trees as shading devices, is that they operate on a relatively gross scale. That is, as long as the weather remains cold during the winter and warm during the summer, these devices remain effective. But in the spring and fall, wide variations can occur and these shading devices cannot respond to meet the changing conditions. If, however, sun control is maintained through the use of an external, operable device, such as an awning or louvers, then, provided the building occupant is willing to take the time to adjust such devices, effective control of the sun can be maintained at all times. Automatic adjustable devices are also available, which allow the sun to enter the building only when the building requires heating.

Use Shading Devices Inside the Window

The most common devices in this category are blinds and curtains. Both of these, operated by the occupant of the building, can reduce the effect of sunlight entering a building. However, because they attempt to control the sun after it has already entered through the window, they are less effective than devices that prevent sunlight from reaching the window.

Light coloured blinds and curtains are more effective than those that are darker because they reflect more sunlight back to the outside [157, 327, 239, 253, 254, 174, 340, 448, 474, 596].

Reduce Internal Loads

In many buildings, the largest component of the cooling load is due to internal generation of heat. Essentially all electrical energy that is used in a building is dissipated as heat; and other major appliances, such as ranges and water heaters, regardless of the form of energy input, contribute significantly to the internal load. In many cases, the reduction of internal loads can be accomplished, at least partly, through physical modifications to the building.

Use Fluorescent Lighting Where Possible

Fluorescent lights use electrical energy approximately three times as efficiently as incandescent lights. In residences, fluorescent lighting is generally limited to use in the kitchen, bathroom and utility areas, since the light is judged objectionably cool for other spaces within a house. In schools and other public buildings, fluorescent lighting can be used in almost all locations.

Automatic Pilot Lights

Pilot lights in gas appliances use as much as 30 percent of the energy for some appliances. The replacement of pilot lights with any of the automatic ignition systems available today would significantly reduce the internal loads.

Proper Ventilation of Heat-Producing Appliances

The relative merits of a recirculating kitchen fan and a vented kitchen fan have already been discussed. The same types of arguments also apply to the clothes dryer, another appliance which generates large quantities of heat when in use.

Install Timers on Light Switches in Infrequently Used Areas

This will prevent the accidental continuous burning of unnecessary lights.

Install Only High Efficiency Appliances in Buildings

A refrigerator can be the highest electricity consuming appliance in a house, but the refrigerator's consumption need not be so high. The least efficient refrigerators available today use approximately three times as much electrical energy as the most efficient. The proper selection of refrigerators, freezers and other major appliances can significantly reduce the internal loads.

The hot water heater is another appliance which consumes large amounts of energy and whose inefficiency contributes to internal loads. Hot water heaters with thicker insulation lose less heat to the house than those with standard amounts of insulation. Also, the hot water heater should be sized properly to reduce unnecessary standby reserves. For example, two people living in a house do not need a 50 gallon hot water heater. In such a case, more water than those two people can use is being kept hot, and more heat than necessary is being lost from the tank into the house provided that the tank is located in the house. Another high-efficiency type of hot water heater is one that is modulating. That is, it has two burners, one to maintain standby conditions, and a larger one for recovery when hot water is drawn from the tank. Since the smaller standby burner would not have to cycle or and off as much as the larger burner, the water heater operates more efficiently [18, 327, 201, 190, 254, 174, 340, 668, 698].

Reduce the Ratio of Building Envelope/Floor Area

Since heat is lost through the area of the building envelope, reducing the area of the envelope without decreasing the floor area of a building would result in a potentially more efficient building. The achievement of the lowest practical building envelope/floor area ratio would be a configuration of building spaces in which length, width, and height of the building are nearly equal.

One negative aspect of this modification is that, for most residential buildings, it would increase the exterior wall area and decrease the roof area. In houses, because the thickness of the cavity of a wall is usually smaller than the thickness in which insulation can easily be installed in the roof, a net reduction in surface area can result in a net increase in heat gain or heat loss [18, 363, 440, 474].

Ventilate Attic Spaces

During the cooling season, the temperature inside an unventilated attic can build up to 20°F or more above the outdoor temperature. This elevated attic temperature causes a greater heat gain through the ceiling than would occur if the attic were vented. The ventilation of the attic should be properly designed to achieve the best results.

- If an exhaust fan is to be installed in the attic, be sure to provide for adequate outside air supply to the attic. If outside air is not adequately supplied, the exhaust fan will draw the cool air from the conditioned space below the attic, causing additional infiltration into the building.
- The control for an attic vent should not sense just the temperature in the attic, but also the outdoor temperature. If the exhaust fan is designed to turn on when the attic temperature reaches some predetermined set point, the temperature outside could be even warmer than the temperature in the attic, in which case the fan would operate continuously until the outdoor temperature dropped, allowing the attic to cool down below the set point of the thermostat. If the thermostat is set high enough so that the outside temperature will rarely exceed the set point, then a rather significant range in which the fan would be beneficial would be eliminated. But if the thermostat senses the attic temperature and the outdoor temperature and activates the attic exhaust fan when the attic is several degrees warmer than the outside temperature, both of the preceding problems are eliminated.

References are [239, 254, 340, 448, 596, 668, 667].

Building and Roof Color

When the sun shines on a building surface, the absorptivity of that surface determines how much of the sunlight will be allowed to enter the mass of the wall or roof and become a potential load on the cooling system or aid to the heating system. The color of the building surfaces determines, in part, the absorptivity of those surfaces.

The determination as to whether building surfaces should be light or dark in color is not necessarily easy. Generally, the cooler the climate the darker the building surfaces should be, since the cooling loads are less important and heating loads are more important. But in most of the U.S., both heating and cooling are important and a detailed analysis of solar effects on a building would be necessary to determine the best absorptivity for the building surfaces [239, 253, 299, 340].

Lower Ceiling Height

Lowering the height of ceilings in a residential building from 8 feet to 7 feet 6 inches produces a corresponding decrease in the surface area of the exterior walls of the building. The reduction in exterior wall area, of course, produces a decrease in the heat gain or loss through the walls.

Other advantages are also achieved with lower ceiling heights. The reduced area of walls, interior as well as exterior, reduces the quantity of materials needed in construction. (In some cases, the savings on materials is not achieved, but is lost in increased waste). Also, the lower ceiling height produces a space with a more intimate feeling than one with a higher ceiling [239, 448, 668].

7.2.3 Modifications to the Heating, Ventilating, and Air Conditioning (HVAC) System

This section will consider modifications to the heating, ventilating and air conditioning (HVAC) systems of a building which result in energy savings. The first part of this section will consider HVAC modifications which have a direct effect on the air change rate in a building. The second part of this section will consider those HVAC modifications which do not directly affect the air change rate.

7.2.3.1 Modifications Which Directly Affect the Air Change Rate

Flue Damper

When a gas, oil, or other combusting furnace is operating, the products of combustion must be allowed to go up the chimney. But when a furnace is not actually burning, the flue does not need to remain open. In fact, if the flue does remain open, heat will be lost through the chimney. An automatic flue damper would close the flue when the furnace is not actually firing. Two different types of flue dampers could be used.

1. Motorized Damper. This type of automatic damper, activated by the same signal that activates the furnace, would open and close as the furnace cycled on and off. A malfunction of this system could cause gases to leak into a building and jeopardize the well-being of its occupants.
2. Differential Pressure Damper. This type of damper is actually opened by the hot combustion gases. As the gases rise in the chimney, they build up pressure below the damper, which then opens to allow the gases to escape. This type of damper also has the advantage that it would prevent downdrafts from blowing out the pilot lights.

References are [299, 596].

Use of Outdoor Air for Combustion

Furnaces are generally installed to use indoor air for combustion, then exhaust the air, with products of combustion, up the chimney. The replacement of the air used for combustion causes infiltration into the building. This infiltration imposes an additional load on the heating system. Therefore, if a building uses a combustable fuel furnace any decrease in the furnace operation will decrease infiltration.

Estimates of the percentage of the entire heating load due to infiltration caused by a furnace range from 3 to 19 percent, depending on the characteristics of the building. The most common values would be near the lower end of this range. The use of outdoor air for combustion would eliminate this cause of infiltration, resulting in lower energy use. This could easily be achieved by installing a duct from the outside to the furnace. A damper would be necessary to prevent a gust of wind from blowing out the pilot light.

The same results could be obtained by changing the heating system from a combusting source, such as gas or oil, to a noncombusting source such as electrical or solar energy [299, 596, 568].

"Economizer" Air Conditioning Cycle

Many types of buildings use enough electrical energy, which dissipates as heat within the building, that the building needs to be cooled even though the outside temperature is lower than the indoor temperature. In such situations, it is advisable to use 100 percent outdoor air for cooling, and exhaust all of the return air, rather than recirculate part of the return air and mix it with some outside air.

One of the aspects of this type of system one must be aware of is that if the controls for the system sense only dry-bulb temperature, the use of the outside air can, in some cases, be wasteful of energy, even if it is cooler than the system's return air. The reason for this is that moisture may have to be removed from the outside air before it is circulated in the building. The removal of moisture from the air, of course, can require a great deal of energy. If the system is controlled by an enthalpy sensor, which takes into account both the dry-bulb temperature and the moisture content of both the return air and the outdoor air, the economizer cycle will be capable of operating only when it is in fact saving energy.

The range of conditions under which an economizer cycle can operate may be expanded if the HVAC system is designed so that return air also picks up internal loads, such as heat given off by lights. In this type of system, the internal loads are intercepted before they enter the space as a cooling load. Instead, they increase the temperature of the return air. Whenever the return air has a higher enthalpy than the outside air, the use of outside air will save energy, so this arrangement of mechanical systems allows an economizer cycle to provide savings even if the outdoor air is slightly warmer than the indoor air [44, 201, 174, 287, 300].

Internal Pressurization

Air infiltrates into a building whenever the pressure outside is greater than the pressure inside. If a building's ventilation system pressurizes the building, a higher exterior pressure must be reached before infiltration occurs. In order to pressurize a building, however, a great deal of mechanical ventilation air is required; thus infiltration through cracks in the building may be reduced, but the air change rate will probably be higher for a pressurized building than for a nonpressurized one.

Filtration and Reuse of Ventilation Air

The controlling factor in determining the quantities of fresh air a space needs is not the physiological need for oxygen, but a comfort factor - the removal of odors and other contaminants in the air. In trying to lower energy consumption, the owners or operators of many buildings have reduced the amount of fresh air introduced into the building. This usually results in an increase in odors present in the building unless a good air filtration system is provided. What is meant by a "good" system is one that is efficient at removing contaminants from the air.

Determining or defining efficiency can be a complex matter because of such variables as particle size, shape, and specific gravity, particle concentration and distribution and air stream velocity. In addition, the ability of a filter to remove dust may vary with time as the filter collects and accumulates the particulate matter. For these reasons, there are several standard test procedures for determining air filter efficiencies. Each standard results in an efficiency of different definition and its application must be carefully considered. In general, three types of tests are employed in determining air filter efficiency.

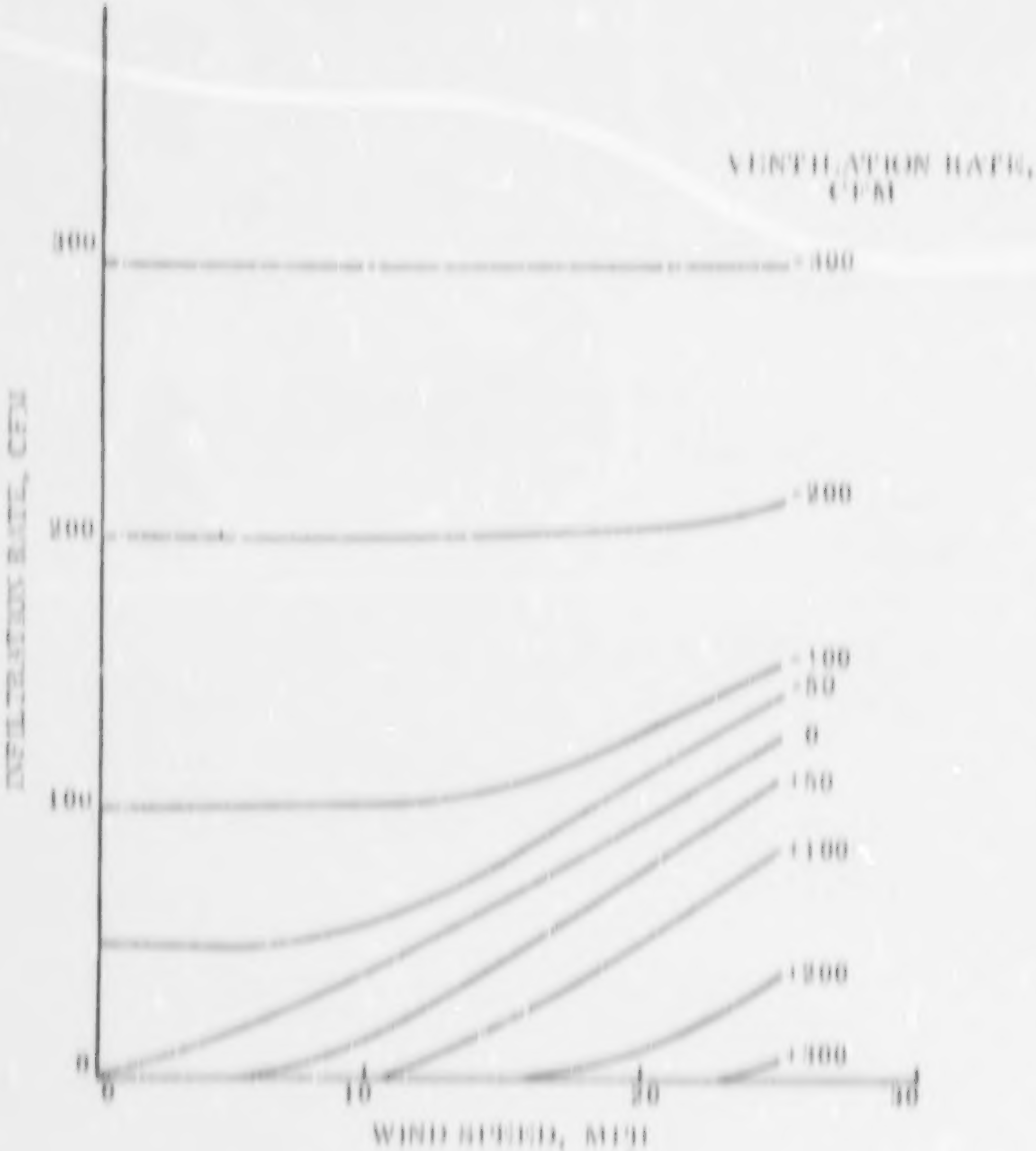


Figure 20. Infiltration rates as a function of wind speed and ventilation rate.

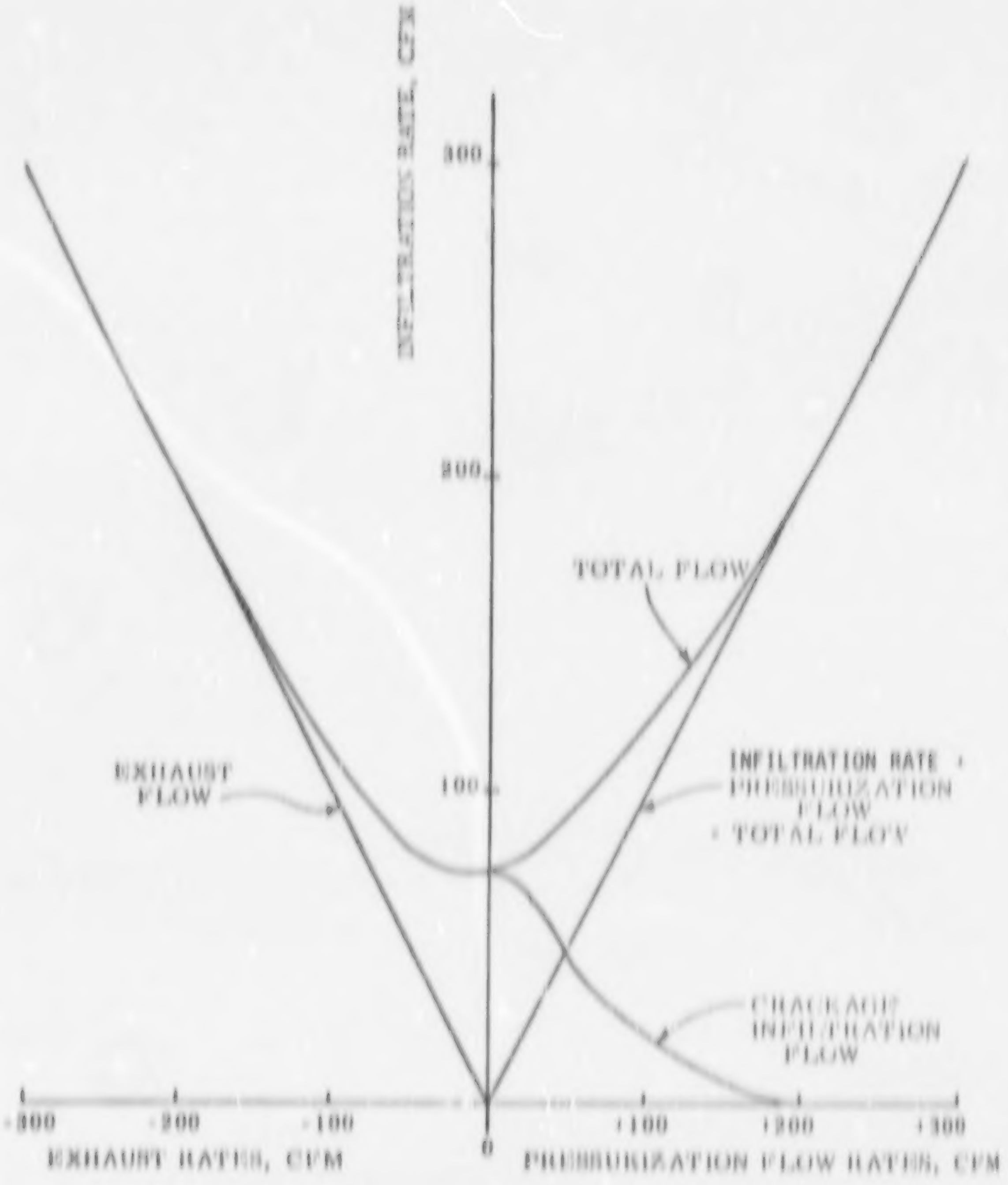


Figure 21. Infiltration rate for a 15 mph wind as a function of ventilation rate.

1. A simple test definition involves passing a cloud of particles of known uniform size, type and concentration through a filter. Measurement of the resulting concentration on the far side of the filter can then be used to define the efficiency. This efficiency gives an indication of the filter's ability to remove only the defined particle size and is useful only for special filtering applications.

2. A similar test, to include an entire size and type spectrum of particulate matter such as found in typical atmospheric air samples, involves passing a standardized dust sample through a filter and determining the efficiency as a result of the weight fraction of the dust collected. The term "arrestance" is often used to describe an efficiency determined as a result of this procedure.

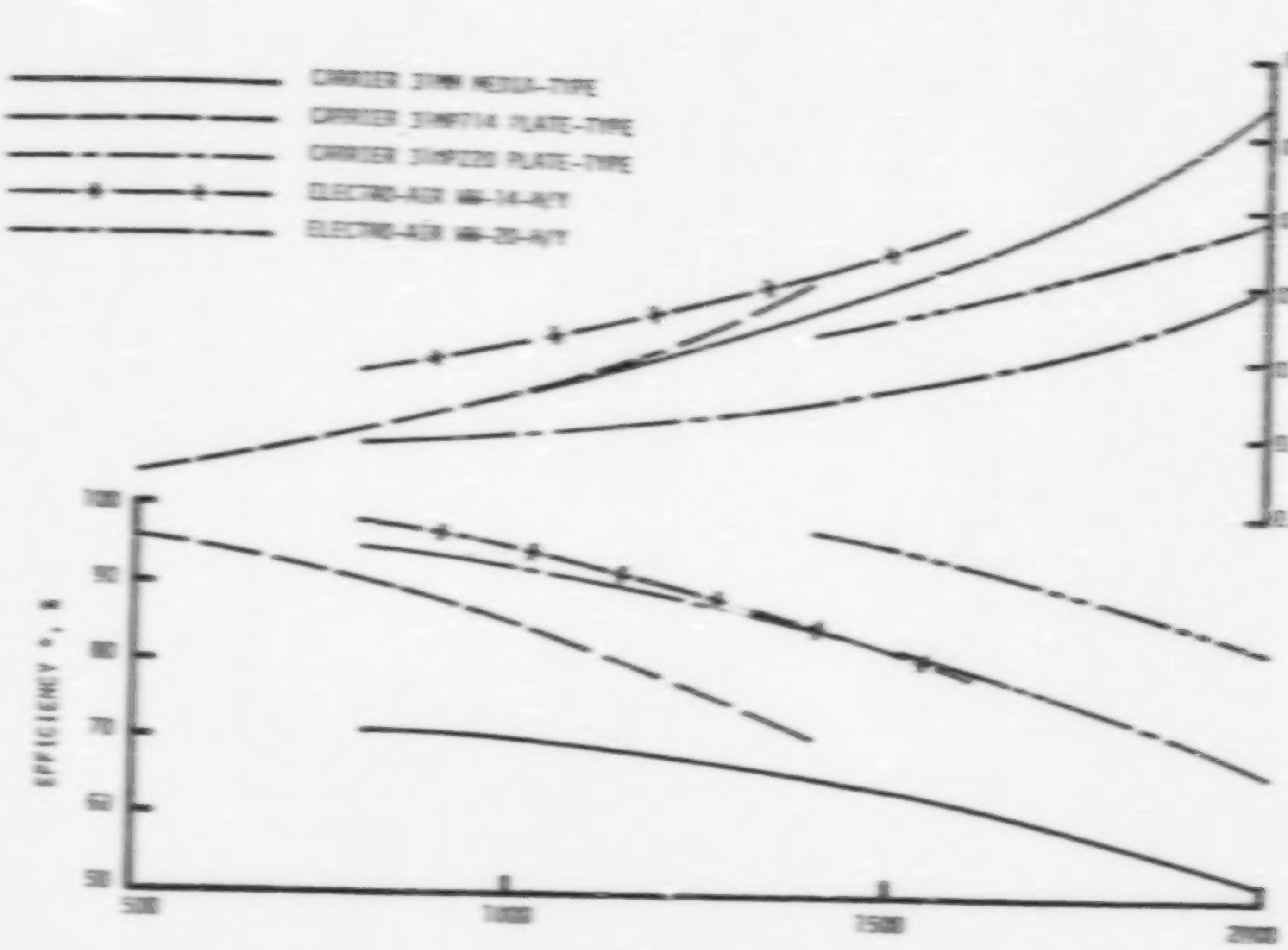
3. A third general category of filter efficiency involves the discoloration effect of air before and after being passed through a filter. This procedure gives an indication of the filter's ability to remove the finer particles within an air sample. This type of testing procedure results in an efficiency often referred to as a "dust spot" efficiency.

When comparing filters used for the cleaning of ventilation or recirculated air for general space conditioning applications, it is useful to know both "arrestance" and "dust spot" efficiencies. These two parameters give an overall indication of a filter's ability to remove atmospheric dust.

Currently, when used in central heating and air conditioning applications, filters with an ASHRAE Weight Arrestance of 85 percent and an ASHRAE Atmospheric Dust Spot Efficiency of 25 percent can be normally expucted as being the most efficient utilized. These are typically dry media, replaceable filters and many times are specified to meet pollen control requirements. Filters normally found on window air conditioners, forced air furnace units, and packaged air conditioned units have substantially lower specifications, typically a 30 percent to 70 percent arrestance and dust spot efficiencies from practically zero to 20 percent. Higher efficiency dry media and electronic air filters are presently available at arrestances near 100 percent and dust spot efficiencies approaching 100 percent. Aside from cost considerations, the use of these high efficiency filters is dependent on two other operating characteristics: air flow resistance and dust holding capacity.

Dry media filters with higher efficiencies have high air flow resistances. This presents a constraint on system air handling requirements. Electronic filters, however, operate at high efficiencies and with air flow resistances tolerable for typical air handling systems. Electronic filters are available for residential HVAC application. These filters operate at spot efficiencies as high as 95 percent, depending on air stream velocity. The maintenance of these filters is dependent on the dust holding capacity. At normal dust-holding capacities, the electronic air filter unit will require frequent periodic cleaning.

Preliminary indications show that the electronic type air filter is probably the most preferable type of air cleaning device for high efficiency residential air purification. Recent developments in electronic air cleaning have led to the availability of this type cleaner for the values of airflow found in residential buildings. Figure 22 shows performance data for a few of the cleaners currently on the market. Among the type represented are the dry media type which contains a replaceable dry media filter for collection, the plate type in which the collection


CARRIER 31MM MEDIA-TYPE
CARRIER 31MRT14 PLATE-TYPE
CARRIER 31MP220 PLATE-TYPE
ELECTRO-AIR WA-14-A/Y
ELECTRO-AIR WA-20-A/Y
PRESSURE DROP IN. WG.
0.30
0.25
0.20
0.15
0.10
0.05
0.0
EFFICIENCY %, %
100
90
80
70
60
50
500
1000
1500
2000
AIRFLOW, CFM

[illegible]

plates are removed to be cleaned, and the water wash plate type (the Electro-air unit) in which cleaning is accomplished automatically by the use of a hot water hook up. NBS Dust Spot Test efficiencies, an indication of the filter's ability to remove the smallest particulate matter, range as high as 96 percent. Figure 30 also gives an indication of expected pressure drop when the filter is installed in various airflow volumes [201, 174, 299].

7.2.3.2 Modifications Which Do Not Directly Affect the Air Change Rate

Recovery of Flue Gas Heat

Furnaces typically operate at about 80 percent efficiency or less. This means that about 20 percent of the heat from the fuel being burned is wasted (much of it going up the chimney) and not contributing to the heating of the building. The heat that is lost up the chimney is in a very high energy state, which makes it relatively easy to recover through heat exchanger devices. Some of the uses to which flue gas heat could be applied are:

1. Preheat Makeup Air. One way to reduce energy consumption in a large building would be to preheat the makeup air with flue gas heat. The use of heat pipes placed in the flues for this purpose would achieve the desired result with no additional energy input. An air to air heat exchanger could also be used for this purpose.
2. Space Heating. Flue gas heat could be used as an auxiliary energy source for space heating using either of the above mentioned techniques, heat pipe, or air to air heat exchanger.

3. Preheat Combustion Air. Flue gas heat can be used to preheat combustion air. By preheating combustion air, the furnace would operate more efficiently, but the heat of the flue gases would not be put to as efficient a use in this purpose as it would if it were used for either space heating or preheating of makeup air.

Refer to [18, 174, 201, 327, 190, 299, 300].

Recovery of Heat from Exhaust Air

Several methods are available for the recovery of heat, both sensible and latent, contained in exhaust air. The most widely used application of heat from exhaust air is to preheat makeup air. This can be done through the use of several devices.

1. Thermal Wheel. A thermal wheel is a device which extracts heat from one stream of air and delivers it to another stream. This is accomplished by the use of a slowly turning wheel. As a segment of the wheel passes through the warmer air stream, it absorbs heat. Then, as the wheel rotates and the warmed segment passes into the cool air stream, it gives up its heat to the air. Thermal wheels can be used to recover both sensible and latent heat.

2. Run-Around Coil. This system is made up of finned tube heat exchangers in the warm and cool air streams (exhaust and make-up), with the heat exchange tubes connected by piping. The system is filled with a heat exchange fluid, normally water and ethylene glycol, which is circulated by a pump. The fluid picks up heat from the warm air and delivers it to the cool air. One of the main advantages of the system is that it can be used even where the exhaust and supply air ducts are in widely separated locations.

3. Heat Pipe. As discussed previously, a heat pipe system can be used in any application where heat must be moved from a warmer location to a cooler location. Heat pipes cannot be used unless the exhaust and make-up ducts are immediately adjacent to each other.

4. Air to Air Heat Exchanger. In this type of system, heat is transferred directly from a warmer air stream to a cooler one by conduction through a common duct wall. A convoluted duct wall, providing a greater heat transfer surface, will make the system more efficient, but normally, the efficiency of this type of system is less than 50 percent.

5. Heat Pump. Using exhaust air as a heat source, a heat pump would be capable of delivering temperatures higher than that of the exhaust air. Additional energy input is required; but when a heat pump has a source that is near 70°F, it can deliver about 3 Btu's for every Btu of electrical energy input.

Refer to [18, 327, 287, 201, 415].

Zone Control of HVAC System

Because different parts of a building are subject to different conditions and uses, they should be divided into separate zones for heating and cooling system design and operation, with each zone individually controlled. In a large building, heat and heat flow in zones near the exterior of the building are affected very significantly by outdoor conditions, e.g., temperature, wind, and direct exposure to sunlight. These considerations do not apply to the interior zones of large buildings, where the temperature (and humidity) may be affected only by the presence of the occupants and their activities, plus, of course, the action of the HVAC system. If the HVAC control system is not free to provide appropriate and different responses to the temperature levels existing in different zones, the building will very likely be an uncomfortable place.

Zone control of lighting is also important. Except in industrial and some commercial applications, gang switching of lights usually results in a waste of energy. Because large areas must be illuminated to allow one person to work, switches should be installed to provide reasonable zone control of lights. The zones for lighting should be carefully planned. Areas near windows should be placed on separate switches since these areas will be able to use daylighting much of the time. Other areas should be divided into the smallest frequently used unit of area which is practical. For example, one switch controlling a room is reasonable in residential applications and in relatively small school rooms. But in larger school rooms, such as the cafeteria, auditorium, etc., more than one switch should be provided for lighting with the room divided into several lighting areas. In offices, each office should have a light switch rather than having many offices controlled by a single switch [18, 44, 201, 254, 174, 596, 667].

Separate Make-up Air for High Exhaust Rate Areas

Building spaces such as kitchens or shops which require a high exhaust rate should be provided with a separate make-up air system. This will reduce the load on the heating system due to infiltration in the rest of the building and will also provide easier control of the conditions in the high exhaust space. This energy conservation modification has been used for a long time in industrial applications for activities such as spray painting, and can be applied to other building sectors without much difficulty [201, 124].

Humidity Control

A properly humidified space can be kept at cooler temperatures in the winter and warmer temperatures in the summer without a detrimental effect on the comfort of the building's occupants. Providing humidity control does require additional energy input, but it is more than compensated for by the reduction in energy input associated with the lower heating and cooling loads due to the modified indoor temperature conditions. In addition, building occupants will actually feel more comfortable, especially in the winter, if humidity control is provided [201, 799, 340].

Equipment Sizing

HVAC equipment works most efficiently when it is operating near full capacity. In this condition, the equipment does not have to cycle on and off as frequently as when the load on the system is much smaller than the capacity. If the HVAC system installed in a building is too large, it will never operate near its capacity, so it will cycle on and off fruquently, which will lower its operating efficiency and increase the wear and tear on the equipment.

In many cases, the application of one or more energy conservation modifications to a building will result in the building's HVAC system being too large. In some cases, such as with a gas furnace, the system might be easily modified so that its capacity is reduced. Other systems are more difficult to modify, and may require replacement to lower the capacity of the system. Since replacement of the HVAC system normally entails a rather large capital expenditure, this modification is usually not cost effective unless the system must be replaced for some other reason [201, 340, 449, 668].

Heat Pumps

A heat pump uses electricity to operate a compressor to extract heat from a low temperature reservoir and transfer the heat to a high temperature reservoir. This process usually uses about one-half of the primary energy requirements of electric resistance heat for favorable operating conditions. The performance of the heat pump declines as outside air temperatures drop below 32°F. There are three reasons for this degradation: the coefficient of performance (COP) is lower, additional energy requirements are needed for defrosting operations, and the change in mechanical properties induce lower efficiencies.

Theoretical analysis shows that the COP is dependent upon the temperature differential between the low and high temperature reservoirs, and that the COP will decrease as the temperature differential increases.

In defrosting operations, the heat pump is operated in the air conditioning mode. This method is universally used in the industry. A typical heat pump will perform well with frost covering 65 percent to 70 percent of the outdoor coil; however the defrost cycle does not need to be initiated until the heat pump's performance is decreased. The following three methods are used to initiate a defrost cycle:

1. Differential temperature initiation
2. Time initiation
3. Air differential initiation.

Differential temperature initiation measures the temperature difference between the outdoor coil and ambient air. Whenever the difference is large, a defrost cycle is started. The problem associated with this mode is that the heat pump could defrost with only 20 percent of the outdoor coil covered with frost and operate many unwanted defrost cycles. Time initiation will start a defrost cycle after a set time interval. Typical time periods are around one hour. This mode will also initiate several unnecessary defrost cycles. Air differential initiation measures the pressure drop across the outdoor coil to initiate a defrost cycle. This method best insures that the outdoor coil is covered with frost and that the system performance is reduced. Although this is a very expensive design, it has the potential to conserve more energy than the two previous modes. Defrost operations consume large amounts of energy, and more effective methods should be developed for energy conservation. It appears that if defrost operations are to be operated in the air conditioning mode, the air differential initiation method is most effective to conserve energy.

The major mechanical problems that affect the performance of a heat pump are the:

- Compressor
- Working fluid
- Maintenance of controls, filters, exchangers and coils.

A typical heat pump has a welded hermetic design, which has a high reliability for air conditioners. However, when used in the heating mode, the compressor operates under greater stress levels at low (32°F and below) ambient temperatures. The welded hermetic compressor will develop temperatures near 275°F in the discharge line. The compressor oil will decompose and create acids at 350°F. The welded compressor has poor heat transfer properties, and common practice has been to flood the compressor with liquid refrigerant. The quantity has to be carefully controlled to allow sufficient liquid refrigerant to cool the compressor, and to avoid large flows that will create lubrication and mechanical problems. The industry has developed a compressor which will operate favorably under the low temperature heating conditions of a heat pump. The new compressor will not develop high temperatures and does not require the periodic flooding of liquid refrigerant. However, this compressor is about twice as expensive as the conventional welded hermetic design. Low maintenance or long-term replacement may justify the added expense. Reliability of long-term data is needed with the present generation of heat pumps.

The working fluid in most of the heat pumps is Freon R-22. This refrigerant performs favorably even though it is not as effective as other refrigerants in heating. The refrigerant, R-22, needs a greater temperature difference response to heat than other refrigerants such as R-12 and R-502. Either of these two refrigerants could improve the heat pump performance in the low temperature heating mode. In addition, the refrigerant R-502 is less expensive than R-22. The substitution of a new refrigerant for R-22 may enhance the heat pump performance to heat, but other operating problems remain that reduce the performance capability of the heat pump.

A typical heat pump requires periodic maintenance and inspection. This will provide for more efficient operation and may enhance the system reliability. A major cause of heat pump failures is related to excessive temperature in the compressor. Flooding the compressor with liquid refrigerant will lower the temperature. Dirty air filters on the inboard coil will create high discharge pressures which will create high temperatures in the compressor and consequently decrease the system reliability. The implementation of an internal pressure relief valve can reduce compressor failures. Periodic maintenance is still required to attain high levels of efficiency and energy conservation.

More efficient components, such as compressor, motor, and fan represent a low level of improvement to heat pumps. A high level of heat pump improvement can be attained with an additional compressor unit. The following cycles represent some of the methods that two compressors may be used to increase the efficiency of a typical heat pump:

- Parallel compression
- Cascade operation
- Series compression
- Two staged.

Parallel compression is a relatively easy method to increase heat pump capacity. Each compressor can be sized differently, and separately controlled to match the heat pump output to the demand. Cascade cycle uses two compressors and two different refrigerants, and can increase the heating capacity. Each compressor operates over half of the temperature range and at a relatively high level of efficiency. Series compression reduces the mechanical and operating losses associated with low temperature heating. The two-stage cycle may also be used to reduce these mechanical and operating losses.

The low level of improvement represents the implementation of more efficient components, while the high level of improvement investigates the potential energy savings of modifications to the standard refrigeration cycle. The effects that these improvements have in reducing the energy requirements for the characteristic structures are presented in Table 34.

TABLE 34. HEAT PUMP IMPROVEMENTS

	Heat Pump Input (Therms)*	
	SFD**	SFA***
Electricity (Thermal) Into Typical Heat Pump (SPF = 2.0)	329	209
Low Level Heat Pump Improvement (SPF = 2.5)	263	167
High Level Heat Pump Improvement (SPF = 3.0)	219	139

* The input are electrical (heat) inputs to heat pumps which are required for the heat pump to satisfy the heating loads of the characteristic residences:

657 Therms for SFD and 417 Therms for SFA.

** Single-Family Detached Housing.

*** Single-Family Attached Housing.

Gas-Fired Furnaces

There are five major losses related to the operation of conventional gas-fired furnaces which cause the seasonal efficiency for a furnace to range from 45 percent to 65 percent:

1. Operating stack loss
2. Jacket loss
3. Cyclic loss
4. Pilot light loss
5. Infiltration loss.*

The operating stack loss is defined as the ratio of the flue losses during furnace cycles to the energy input of the fuel and is usually about 25 percent. Problems of condensing water vapor and ensuing acid formation in the flue may exist if the stack loss is reduced. There are two methods to reduce the operating stack loss, which are (1) more efficient energy transfer from the fuel to the conditioned air, and (2) the implementation of a heat recovery device in the flue. The furnace can reduce the operating stack loss to 20 percent through the designs of more efficient burners and improved heat exchangers without creating any flue problems. A heat recovery device can be placed in the flue to transfer some energy from the flue gases to the conditioned air. The device can lower the operating stack loss to a range from 13 to 21 percent.

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* Infiltration loss is expressed as the increase in infiltrated air, used for furnace combustion air.

The jacket loss is no more than about 0.2 percent and the potential energy savings which may be attained are small.

The cyclic loss, which can be as large as 10 percent, is defined as the ratio of the energy losses due to start and warm-up operations. The energy losses are due to the cooling of the heat exchanger and can be affected by the fan temperature settings. The cyclic losses may be reduced to about 2 percent by lowering the temperature setting for the fan. The potential energy savings for the cyclic losses is also dependent upon the type, capacity, and proper sizing of the furnace to the actual operating conditions.

The pilot light loss may range from 5 percent to 19 percent and can be eliminated by the implementation of electric ignition devices. An electric ignition device ignites the pilot light whenever there is demand for heat. A sensor prevents gas flow to the main burners unless the pilot light is burning. The pilot light will only burn during main burner operation and can reduce the entire pilot light loss.

Conventional furnaces are naturally aspirated and draw the combustion air from the air conditioned space. Infiltration air replaces air used in combustion and can represent up to 10 percent of the total infiltration of the residence. There are two methods of eliminating the infiltration loss. The outside air may be directly vented to the furnace for combustion air or the furnace could be located outside the structure. Either of these methods eliminate the infiltration loss. A 10 percent reduction in infiltration reduces the heat load of the characteristic residences by 22 therms and 14 therms for SFD and SFA units, respectively.

Other factors affect the seasonal efficiency of a furnace. The majority of furnaces are not properly sized to meet the peak heating load. In many installations, the furnace capacity is oversized by a factor of 2. The application of a properly sized furnace could reduce the annual heating requirement by up to 10 percent. The energy savings for houses which have been retrofitted with better thermal insulation may be enhanced by the implementation of a new properly sized furnace which is based upon the peak heating load of the retrofitted house. Properly sized furnaces could reduce the heating energy requirement up to 88 therms and 56 therms for SFD and SFA residences, respectively.

Innovative gas-fired furnace designs may have the potential to conserve energy. One manufacturer is currently marketing a furnace that has a unique burner. The furnace is located exterior to the house and the exhaust gases are released directly to the environment. The burner is smaller than conventional units and has improved heat transfer properties. The potential energy savings are up to about 19 percent in comparison to conventional naturally aspirated gas furnaces (internal to residence). Another design is a pulse combustion furnace. From 1956 to 1958, pulse combustion boilers were manufactured for residential hydronic space heating systems (experimental tests show that the steady state efficiency ranges from 95 percent to 98 percent). The pulse combustion boiler can achieve energy savings from 24 percent to 40 percent in comparison to a conventional gas furnace in actual installations in similarly constructed residences.

The low level of furnace improvement has an improved heat exchanger and furnace combustion air source external to the residence. The high level furnace improvement represents a typical furnace with an improved burner design. The energy savings associated with these improvements are shown in Table 35.

TABLE 35. GAS-FIRED FURNACE IMPROVEMENTS

Furnace	Furnace Inputs (Therms)[1]	
	SFD	SFA
Low Level Furnace Improvement	709	430
High Level Furnace Improvement	692	419

[1] The furnace inputs or gas (heat) inputs to furnaces which are required for the furnace to satisfy the heating loads of the characteristic residences: 657 Therms for SFD and 417 Therms for SFA.

The furnace improvements resulted in the following energy requirements reductions:

	Percent Reduction in Fuel	
	SFD	SFA
Low level furnace improvement	19%	19%
High level furnace improvement	21%	21%

Oil-Fired Furnaces

The design of conventional oil-fired furnaces is very similar to the conventional gas-fired furnaces. Many of the technical options for the gas-fired furnace are applicable to the oil-fired furnace, and the potential energy savings may also be very similar. The operating condition of an oil-fired furnace is more critical so that annual maintenance is more important to conserve energy. One technical option that may be implemented for oil-fired furnaces is emulsified fuels. The fuel could be a mixture of oil and water or a mixture of oil and methanol. The fuel mixture can be emulsified by (1) mechanical mixing, (2) ultrasonic emulsification or (3) spray techniques. Current research has developed an ultrasonic cavitation technique to produce water-in-fuel emulsion immediately before combustion. There are advantages for its application in residential furnaces. The excess combustion air could be reduced by 50 percent and have lower particulate emissions. The surface of the heat exchanger had fewer carbon deposits. The conclusions from contemporary studies indicate that increased fuel oil furnace efficiency could be attained at significantly reduced air and fuel flows. These potential energy savings enhance the applications of emulsified fuels in residential furnaces.

A low level of improvement can be attained by a modified burner design. A high level of improvement can be attained through use of a fuel emulsifier unit installed into the oil-fired furnace. These improvements may reduce the heating requirements, and are presented in Table 36.

TABLE 36. OIL-FIRED FURNACE IMPROVEMENTS

Furnace	Heating Requirements (Therms)	
	SFD	SFA
Output	657	417
Characteristic Furnace Input	939	596
Input to Low Level Improved Furnace	821	521
Input to High Level Improved Furnace	747	474

The furnace improvements result in the following energy savings [299].

	Percent Reduction in Heating Requirements	
	SFD	SFA
Low level furnace improvement	13%	13%
High level furnace improvement	20%	20%

Mix-Mode Heating Systems

Heat pump manufacturers are currently offering a heat pump package to assist a furnace for space heating. The heat pump would supply all the heating requirements down to its balance temperature (about 40°F). Below this temperature, the furnace would supply all the heat. Two benefits result from this mode of operation: (1) the heat pump has very high COP's at moderate temperature differentials, and (2) the cyclic losses for the furanre would also be reduced. The energy saving potential ranges from 10 percent to 5 percent. The actual energy savings depend upon climate, as well as other factors [299].

7.2.4 Building Operation Modifications

7.2.4.1 Modifications Which Directly Affect the Air Change Rate

Reduction in Percentage of Outdoor Air Intake

Many HVAC systems operate using an arbitrary percentage of outdoor air which is much higher than necessary. A reduction in the percentage of outdoor air intake would lower heating and cooling loads, and help control humidity. In some cases, a reduction of outside air intake would necessitate the addition of an air cleaning device to maintain tolerable levels of odors in the building. (Air cleaning devices are discussed in the previous section, Modifications to the HVAC System.) Refer to [327, 201, 190, 174].

Reduction in Ventilation Rate

A reduction in the ventilation rate would also bring about a reduction in the amount of outside air brought into a building. The percentage of outside air would remain the same, but the quantities of air being handled would be reduced. The reduction in volume of air to be handled would allow a reduction of fan size, saving operating energy requirements. Also, by reducing the quantity of outdoor air introduced into the building, the heating and cooling loads would be reduced. Reduction of ventilation rate is not a modification that is universally applicable. If the ventilation rate is already near its minimum, a further reduction would require either an auxiliary odor control mechanism or an auxiliary heating/cooling mechanism [18, 201, 174, 547, 667].

Night Shutdown of Outdoor Air Intake Dampers

During the night, and on weekends and holidays, many nonresidential buildings have little or no occupancy. For these periods, it is unnecessary to mechanically introduce outside air because there are few odor-producing or oxygen consuming activities. The small needs for fresh air would certainly be provided by infiltration of outdoor air into the building. The elimination of mechanical ventilation of the building with outside air can significantly reduce the energy consumption in the building for heating and cooling operation modes [201, 190, 174].

Time Clock Ventilation Control

During hours when a building is unoccupied, or experiences limited occupancy, ventilation is unnecessary. In buildings which have a regular schedule of activity, the hours of ventilation operation can easily be controlled by a time clock to coincide with the hours of use of the building. By shutting down the ventilation system at night, or other unoccupied times, savings are achieved in two ways:

1. The energy normally required to run the fans would not be used.
2. The ventilation system shut down would eliminate mechanically induced infiltration.

References are [201, 174, [illegible]].

Zone Control

If a building's mechanical system is provided with zone control, it does not save energy unless the system is used properly. The building operator must be aware of the different conditions in each zone and the requirements imposed by the activities which occur in each zone. A school cafeteria, for example, needs relatively high ventilation and can be set at a lower temperature than classrooms [18, 44, 201, 254, 174, 596, 666].

Computer Control

In a large building, it is desirable not only to have each zone responding individually to the conditions of that zone, but for the HVAC system as a whole to work in its most efficient manner. Means are now available to control an entire building's HVAC system through a computer. Programs to do such things as automatically turn off equipment in a predetermined priority order as loads become too large, or respond to outdoor conditions before they begin to affect the interior conditions are available [201, 190, 287].

7.2.4.2 Modifications Which Do Not Directly Affect the Air Change Rate

Nighttime Temperature Setback

Nighttime temperature setback has been cited as a very easy and effective method to reduce energy consumption. Utility companies frequently make statements indicating that a savings of 1 percent of the heating fuel bill can be saved for each 1°F the thermostat is turned down at night. Studies have indicated as much as 15 percent savings of the heating fuel bill for an 8°F nighttime setback. Because of the response of the building to the temperature setback, the savings realized in a well-insulated building would be, on a percentage basis, greater than the savings in an uninsulated building. This is due to the relatively long time it would take for the temperature in a well insulated building to fall to the lower thermostat setpoint, and to the shorter recovery time in the morning to raise the temperature again. Clock thermostats are available which automatically reduce the setpoint in the evening and increase it in the morning so that the building occupants do not have to constantly adjust the thermostat. [327, 201, 254, 174, 287, 340, 501, 596, 668, 667, 719].

Regular Maintenance of System

By maintaining the HVAC system, it will operate at its maximum efficiency. Some of the items that should be on a maintenance checklist broken down by system type are:

- Oil Furnace
    - Adjust and clean burner unit
    - Adjust fuel-to-air ratio for maximum efficiency
    - Check for oil leaks
    - Check electrical connections, especially on safety devices
    - Clean heating elements and surfaces
    - Adjust dampers and draft regulator
    - Change oil filters
    - Change air filter
    - Change oil burner nozzle
    - Check oil pump
    - Clean house thermostat contacts and adjust

    Tests for furnace efficiency:

    - Draft test to see if heat is being lost up the chimney or if draft is not enough to properly burn the oil
    - Smoke test to see if the oil is being burned cleanly and completely
    - CO_2 test to see if fuel is being burned completely
    - Stack temperature test to see if stack gases are too hot or not hot enough
- Coal Furnace
    - Adjust and clean stoker
    - Clean burner of all coal, ash and clinkers
    - Oil the inside of the coal screw and hopper to prevent rust

- Gas Furnace
  - Check operation of main gas valve, pressure regulator and safety control valve
  - Adjust primary air supply nozzle for proper combustion
  - Clean thermostat contacts for proper operation.

The draft test and stack temperature tests for efficiency are also applicable to a gas furnace [2, 327, 201, 254, 174, 313, 598, 667].

Scheduling of Custodial Operations

One way a great deal of energy can be saved is by scheduling custodial operations to overlap with normal daily activity. This reduces the requirements of keeping lights on when very few people are in the building. If custodial operations cannot be scheduled to overlap the daily building activities, they should be performed in such a way as to minimize the number of lights needed at any time [201, 190].

7.2.5 Life Style Factors

7.2.5.1 Modifications Which Directly Affect the Air Change Rate

Indoor "Fresh Air" Habits

The effects of almost any energy conserving feature which can be installed in a building can be negated by the occupants' opening of windows for fresh air. Even if the windows are closed, infiltration may account for nearly half of the heating load, so if the windows are opened to provide more fresh air, the part of the heating load due to infiltration will increase enormously [299].

Use of Kitchen, Laundry and Bathroom Vents

Even if vents are provided, they are ineffective unless properly used. When an appliance which generates heat and moisture is used, it should be vented to the outside in the summer, and allowed to dissipate its heat inside in the winter. The use of a vent to discharge heat in winter should be avoided [299].

Entry and Exit from Buildings

The length and numbers of time doors are opened, either in entry and exit or for "fresh air" will have a large effect upon the infiltration of outdoor air into the indoor environment. Just as open windows can increase energy consumption during the heating and cooling seasons the extent of increased infiltration of outdoor air through open doors will have the same effect.

7.2.5.2 Modifications Which Do Not Directly Affect the Air Change Rate

Indoor Temperature and Humidity Settings

In the 1920's, 70°F was the average indoor design temperature. Between that period and 1970, the indoor design temperature increased by about 1°F per 10 years until it reached 75°F in the early 1970's. The recent energy crisis has caused a drop in the indoor design temperature to 68-70°F, a temperature range that many people are finding to be comfortable and economical. Studies have shown a savings of approximately 3 percent of the heating fuel bill for each degree F the thermostat setting is lowered.

The same principles hold true for cooling. The temperature and humidity controls should be set at the maximum comfortable level to achieve energy savings [2, 18, 327, 190, 174, 596, 598, 667, 719].

Use of Appliances

The use of heat-generating appliances should be limited during the cooling months. The reduction of use of appliances such as range and dishwasher would result in direct energy use reduction and an indirect reduction because of reduced loads on the cooling system. When heat-generating appliances are used during the cooling season, an exhaust fan should also be used [299].

Lighting Levels

Most buildings are over-illuminated. This demonstrated by the number of buildings in which lights were recently removed to reduce energy consumption. The requirements for lighting for particular tasks is usually given in design books as a range of values. Until a few years ago, most designs used the upper limit of the design range. Today, more designers are using values that are lower in the range for a particular task [16, 327, 190, 174, 547, 254, 698].

Turning Off Unneeded Lights

When activity is not occurring in a space, it is usually advantageous to turn out lights. This is almost always true for spaces lighted with incandescent bulbs, and it is true for spaces with fluorescent lighting if the duration for which the lights will remain off is longer than about 30 minutes. If the duration is shorter than 30 minutes for fluorescent lights, the cost for replacing the tubes due to shorter life starts to approach the energy savings.

One of the places turning off lights can be very effective is in schools. When one class leaves a room, the lights are usually left on for the next class, but sometimes the next class will not use the room for several hours [18, 327, 190, 174, 668, 697].

Use of Operable Shading Devices

If awnings, blinds, curtains, or other operable shading devices are available for a building occupant to use, the occupant should learn how to use the device and then use it. By using operable shading devices, direct sunlight can be excluded from the building when it is not desired, and admitted when it would be beneficial [299].

Use of Operable Insulating Shutters

If a building has insulating shutters installed on its windows, their use by the building's occupant can greatly reduce the energy required to heat or cool the building. In residences, for example shutters could be closed at night instead of curtains, and the modification of life style would be minimal. Of course, the shutters should be designed to be easily operated for safety [299].

7.3 BUILDING CLIMATOLOGY AND RELATIONSHIPS BETWEEN INDOOR AIR QUALITY AND HVAC SYSTEMS

Indoor air pollution behavior has been shown in earlier sections of this report to be related to the indoor-outdoor air exchange rate of a building. Subsequently, in Section 9.0, Modeling of Indoor Air Pollution Behavior, this relationship will be discussed in detail. Energy conservation modifications which affect air exchange rates will also affect the behavior of indoor air pollution concentrations. Further, many energy conservation measures are implemented through the operation of the building heating, ventilation and air conditioning (HVAC) system, which may contain filters and other devices for cleaning polluted air. The performance of these cleaning systems may be altered by adjustments of air flow for energy conservation purposes, thus impacting upon indoor air quality. One aspect of this, the filtration and reuse of ventilation air, has already been described in Section 7.2.3, with a discussion of the measurement of efficiency of filters for particulate removal. A further discussion appears in later pages in Section 7.3.2. But before continuing with the relationships between energy conservation and air quality, it is appropriate to review briefly the influences of temperature and humidity (whether controlled by an HVAC system or uncontrolled) upon indoor air quality. This is the subject of the next section.

7.3.1 Building Climatology

Building climatology may be defined as the regime of temperature, humidity, and air movement which prevails within the building. It may vary within the building from zone to zone. Building climatology is affected by outdoor ambient meteorology (temperature, humidity, wind speed and direction, insolation), building structural characteristics, building use and occupancy and the design and functioning of the HVAC system.

The indoor climatology in turn affects the behavior and impact of airborne pollutants within the building. Temperature gradients within the building, and between the indoor and outdoor environments, affect the flow of air in the building and hence the flow and dispersion of air pollutants.

The ASHRAE Handbook of Fundamentals [22] provides an empirical relationship which indicates how the indoor temperature affects the air flow through the buildings:

$$Q = 9.4\ A \sqrt{h\ (t_o - t_i)}$$

where

Q is the air flow rate

A is the free area of inlets or outlets

h is the height from inlets to outlets

t_i is the average temperature of indoor air between the elevations of the inlets and outlets

t_o is the temperature of outdoor air.

This flow of air in a building resulting from the indoor-outdoor temperature difference, as described here, is referred to as the stack effect in ventilation studies [22].

The flow of air occurring in the "stack effect" is derived from infiltration, the entry of air into a structure from outdoors. The difference between indoor and outdoor temperature, a climatological parameter, affects the infiltration rate and consequently the indoor air pollution levels. Figure 23 reproduced below provides experimental data that illustrate the relationship between air infiltration and the temperature difference between the ambient temperature and the indoor temperature.

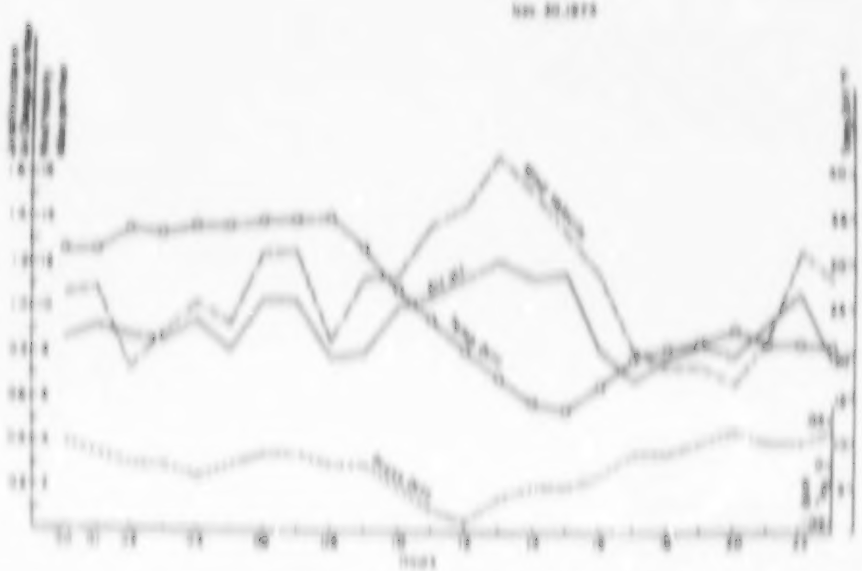


Figure 23. Experimental data illustrating the influence of the building climatology on the air infiltration [275].

Indoor temperature and relative humidity both influence the chemical reaction rates and the rates of decay of concentrations of indoor pollutants. The pollutants which have received the greatest amount of attention in their indoor chemical behavior are the photochemical oxidants and SO_2. Much of the research has taken place in laboratory environments, in well regulated chambers. Mueller et al. [419] performed a series of experiments to determine the ozone decomposition rate for various indoor spaces. Their findings on the decay constants and the half-life of ozone as a function of temperature and relative humidity in an aluminum chamber and in various enclosed areas are illustrated below in tables 37 and 38:

TABLE 37. EFFECT OF RELATIVE HUMIDITY ON OZONE DECOMPOSITION IN ALUMINUM CHAMBER [459]

Volume of Chamber = 76.6 ft^3

R.h. (%)	Temperature (°F)	First-Order Decay Constant (min^{-1})	Half-Life (min)
5	73.2	0.0014	495
23	78.8	0.0015	462
48	80.0	0.0029	239
55	80.0	0.0034	204
66	79.3	0.0060	115
87	79.2	0.0574	12.1
87	79.2	0.0541	12.8

TABLE 38. SUMMARY OF RATE CONSTANTS OBTAINED IN VARIOUS ENCLOSED AREAS [459]

Flow Rate = 280-300 cfm
Temperature = 70-80 °F
R.h. = 26-50 Percent

Test Area	First-Order Decay Constant (min^{-1})*	Half-Life (min)
Decay of ozone in room without carbon filter		
Aluminum room, 420 ft^3	0.058 ± 0.004	12
Stainless steel room, 525 ft^3	0.025 ± 0.002	28
Bedroom, 1440 ft^3	0.121 ± 0.006	5.7
Office, 1950 ft^3	0.063 ± 0.002	11
Decay rate with activated carbon filter in air cleaner		
Aluminum room, 420 ft^3	0.465 ± 0.010	1.5
Stainless steel room, 525 ft^3	0.323 ± 0.010	2.1
Bedroom, 1440 ft^3	0.225 ± 0.016	3.1
Office, 1950 ft^3	0.107 ± 0.008	6.5

* Rate constant with 95 percent confidence limits.

The Mueller et al. [439] study monitored the decomposition rate of ozone in several metal test facilities in an office and a home. The following statements are quoted from the discussion summarizing the findings of this work.

- "The decomposition of ozone was found to follow first-order kinetics in an aluminum chamber, an aluminum room, a stainless steel room, an office, and a bedroom.
- "The rate of ozone decay was dramatically altered by variations in humidity or temperature. Increasing either the humidity level or the temperature enhanced the rate of ozone decay.
- "The rate of decomposition in an aluminum chamber and stainless steel room decreased with continuous exposure to ozone. The metal surfaces appeared to become seasoned toward this oxidant.
- "The half-life of ozone in a typical bedroom was rather short (6 minutes) suggesting that this pollutant decomposes rapidly after it enters typical living spaces.
- "Activated carbon was shown to be effective in removing ozone from a flowing airstream. The carbon filter increased the rate of decay and lowered steady-state ozone levels in a closed room when placed directly downstream from an electrostatic precipitator."

A unit commonly used for first-order decay contents is the volume per unit area per unit time (ft^3/ft^2-min), in this unit the rate constants for the ozone decay, taken from the table are: aluminum room, 0.054; stainless steel room, 0.031; office, 0.073; bedroom, 0.122. Given the difficulties involved in measuring the true surface areas in living spaces the last two decay constents should be considered as upper limits of the quantity.

A study by Cox and Penkett [144] investigates the "Effect of Relative Humidity on the Disappearance of Ozone and Sulfur Dioxide in Contained Systems." If the absorption of the pollutant by the room's walls is irreversible, which is assumed to be the case, then the best method of estimating relative values is in terms of deposition velocities. This quantity is defined as follows:

$$V_g = \frac{\text{Total deposition per unit area}}{\text{Time integral of volumetric concentration}}$$

While V_g is independent of the surface to volume ratio, it does depend on fluid flow considerations. V_g is connected to the decay constant, k, by the relationship: $V_g = k/r$, where r is the surface to volume ratio. For a first order process the half-life is related to the decay constent by $t_{1/2} = 0.693\ k$. The Cox, Penkett study [144] presents values for $t_{1/2}$, k, and V_g for ozone and sulfur dioxide in two separate containers as a function of the relative humidity. The "disappearance" of ozone and sulfur dioxide followed a first-order decay. The straight lines in the semilogarithmic plots of concentration versus time, in Figure 24 below indicate the irreversible nature of the chemical reactions.

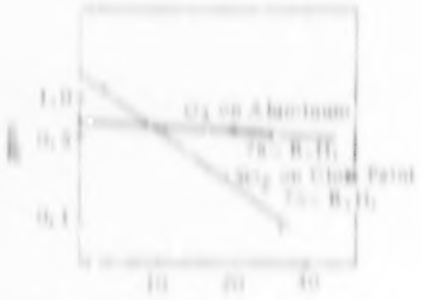


Figure 24. Typical decay curves for sulfur dioxide and ozone [144]

TABLE 39. VALUES FOR k, $t_{1/2}$, AND V_g AT VARIOUS RELATIVE HUMIDITIES [166]

SO_2 on Steel Plate				SO_2 on Aluminum				Ozone on Aluminum			
R.H. (%)	$t_{1/2}$ (min)	k (min^{-1})	V_g ($cm\ s^{-1}$)	R.H. (%)	$t_{1/2}$ (min)	k (min^{-1})	V_g ($cm\ s^{-1}$)	R.H. (%)	$t_{1/2}$ (min)		
31	100	6.93×10^{-3}	1.16×10^{-3}	11			1.5×10^{-3}*	30	100	3.51×10^{-3}	6.09×10^{-3}
60	11.5	6.03×10^{-2}	9.13×10^{-3}	61			3.5×10^{-3}*	55	105	5.56×10^{-3}	6.13×10^{-3}
66	8.6	8.07×10^{-2}	5.99×10^{-3}					73	80	8.67×10^{-3}	1.00×10^{-2}
79	6.3	1.06×10^{-1}	2.93×10^{-2}					81	63	1.12×10^{-2}	2.06×10^{-2}
86	5.3	1.30×10^{-1}	5.09×10^{-2}	76	6.3	1.50×10^{-1}	6.66×10^{-3}				

* Data also due to Spedding (1969).

A detailed review of the photochemical aspects of air pollution by Altshuller and Bufalini published in 1971 [8] includes a series of studies that report on the relative humidity effects on a number of photochemical processes. An example from this study which illustrates both the importance of relative humidity in photochemical reactions and the difficulty involved in quantifying its effects is shown in the table of reactivity levels below, from Dimitriades [8], which suggests that NO oxidation is very sensitive to changes in relative humidity. In a subsequent study, Dimitriades [8] presents data which show no systematic humidity effect; he notes that there are many other factors that must be considered.

TABLE 40. REACTIVITY LEVELS FROM IRRADIATION OF 1.83 ppm C ETHYLENE + 0.30 ppm NO IN THE PRESENCE OF VARIOUS WATER-VAPOR LEVELS

H_2O (mm Hg)	Relative Humidity at Room Temperature (77°F) (%)	Relative Humidity at Chamber Temperature (97°F) (%)	Reactivity Index			Maximum Ozone Level (ppm)	Maximum Ozone Formation Rate (ppm/min)
			R_{NO_2} (ppm/min)	Ozone (ppm × min)	HCHO (ppm × min)		
0.0	0.0	0.0	0.0101	33.7	133.0	0.32	0.0014
2.9	12.3	11.7	0.0083	28.5	151.9	0.37	0.0017
7.2	30.3	21.3	0.0051	53.3	165.5	0.38	0.0022
11.5	48.9	38.5	0.0084	48.5	171.7	0.47	0.0033

The relations between the building climatological parameters and the chemical behavior of the indoor pollutants are best studied in laboratory chambers. The advantage of utilizing such an experimental technique is related to the complete control of the chamber's temperature, relative humidity and other environmental factors. It is however very difficult to extrapolate chamber data to real conditions in buildings.

It is apparent that energy conservation measures which change the temperature levels or humidity levels in buildings will also have some effect upon the chemical reactivity and decay rates of reactive indoor air pollutants such as oxidants and SO_2. It is not clear, on the basis of identified research, what the resulting impacts will be in a complex building environment.

7.3.2 Energy Conservation and Indoor Air Quality

As suggested in the previous paragraph, the search for published material on the effects of energy conservation measures on indoor air quality produced very little. What was found indicated that the primary effect of energy conservation on indoor air quality is due to a decrease in ventilation and infiltration rates in buildings rather than to indoor climatological changes. Such measures, while reducing the effect of outdoor sources of pollution, increase the effect of indoor-generated pollutants. The increase in concentration of most indoor-generated air pollutants as a result of decrease in ventilation and infiltration-exfiltration would be difficult to estimate because the emission rates of the pollutants are very poorly understood. However, one study indicated that approximate increases in level of indoor-generated particulates, due mostly to smoking, could be expected to occur as follows as air exchange rates are reduced [44].

Type of Building	Average Reduction of Ventilation and Filtration	Approx. Increase and Concentrations of Particulates
Single-family residence	3.5%	4%
Multi-family residence	45%	82%
Schools	45%	82%

The same study, by Arthur D. Little [44] presents a concise description of the techniques by which indoor air pollutants may be removed through HVAC system operations. The authors state that coarse particulates (larger than 2 μm diameter) can be removed by sedimentation, electrostatic precipitators, filters, and aqueous sprays. Fine particulates (smaller than 2 μm diameter) pass through many types of air cleaning equipment and settle very slowly in air. Citing earlier work the authors note that reactive gases, such as sulfur dioxide and ozone, can be removed by reaction with furnishings, structure, aqueous sprays, and adsorbent filters [65, 439, 534]. Less reactive gases, such as carbon monoxide and hydrocarbons, are more difficult to remove.

Major air cleaning techniques described by Arthur D. Little as being applicable for use with HVAC systems (and hence subject to adjustment of operating modes in energy conservation modifications of HVAC systems) were:

> Filtration. Filters range from the common low efficiency hot air furnace filter to the high efficiency particulate air filter.

Electrostatic Precipitation. Electrostatic precipitators for particulates generally have high efficiencies and low air resistances. They can generate small quantities of ozone.

Air Washers. These are generally of the spray type or packed cell type. They can remove particulates and SO_2.

Gas Sorbents. Activated carbon has been used to remove odors and ozone and is used in electrostatic room air cleaners to remove ozone. They can remove SO_2.

A discussion of the role played by filters (or other air cleaning devices) in the mathematical modeling of indoor-outdoor air pollution concentrations appears in Section 9.0 of this report. Through mathematical modeling it should be possible, at least theoretically, to relate a reduction in ventilation-infiltration-exfiltration rates, planned for energy conservation purposes, to changes in (1) the chemical decay rates of reactive pollutants, as a result of changes in indoor temperature and humidity, (2) the dilution, dispersion and physical removal of indoor pollutant concentrations, as a result of changed air flow patterns within the building and through its indoor-outdoor perimeter and (3) the rates of pollutant removal in filters, precipitators, air washers and sorbents in the HVAC system, as a result of changed rates of air flow through the HVAC system ducts.

Section 8.0
HEALTH EFFECTS

The concern for human health is the principal reason for research in indoor air pollution. It has been shown that air pollutants occur in indoor environments at concentration levels which differ from the outdoor, ambient concentrations of the same pollutants. The indoor concentrations may be either higher or lower than the outdoor. An initial health effects research question is: To what extent is the existence of this indoor air pollution a hazard to human health? A subsequent question, dependent upon results of the first, is: What actions can be taken to mitigate the hazard? Research addressing the first of these questions is the subject of the present chapter, Section 8.0. The second question is not frontally addressed, although an approach toward it through modeling is discussed in Section 9.0.

Sections 3.0 and 4.0 have identified work of various investigators in measuring indoor air pollution concentrations. The measurements have typically been for short-term durations, ranging from instantaneous peaks to 1-hour and 24-hour averages. Health impact is a function of human exposure to pollution. Exposure may be defined as the product of air pollutant concentration and the time in which an individual is exposed to the concentration. The health effects associated with exposure may vary with the intensity and with the duration of the exposure, as will be brought out in subsequent discussions. Studies of the nature and duration of human occupancy of indoor spaces, an essential element in determining exposure, have been reported in Section 6.0. Relevant research data are limited in extent. As will appear, the existing observational data on short-term indoor concentrations of a limited number of air pollutants, and probable resulting exposures, are inadequate as a basis for definitive conclusions about the magnitude of the health problems which may exist as a result of indoor air pollution. But comparisons of the limited, available indoor air quality data with results of research into the health effects of ambient pollutants, and with research into health effects of air pollution in some industrial workplace contexts, will confirm that indoor air pollution in nonworkplace environments does reach levels at which human exposures resulting in adverse health impacts may occur. The evidence for this, as reported in the scientific literature, is discussed in what follows.

The scope of the health effects section of this report was defined at its outset as a comprehensive review of the state-of-the-art, described in published literature and unpublished ongoing research, of knowledge of the health effects of those indoor air pollutants for which studies of indoor concentrations and behavior have been made. Subgroups of populations which have demonstrated increased sensitivity to those pollutants, and evidence for additive, synergistic or antagonistic properties of the pollutants with respect to health status, were to be described. The extent of available information was to be evaluated, and areas of current research and research gaps identified. Findings from the review were to be incorporated into an overall appraisal of the potential impact of indoor air pollution, with a relative ranking of the hazards from different indoor air pollutants.

To address these questions a review and discussion are presented under the following headings:

- Sulfur oxides
- Carbon monoxide
- Carbon dioxide
- Nitrogen oxides
- Photochemical oxidants
- Organic pollutants
- Particulates
- Air pollution and lung cancer
- Susceptibility of population subgroups
- Interactive pollutant effects
- Evaluation of indoor air pollutant health hazards and research priorities.

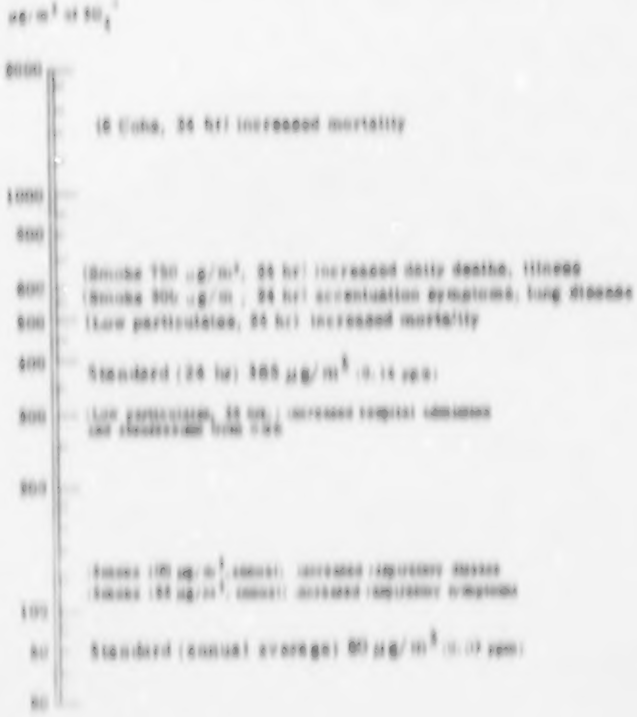
These headings and the defined scope of the review are ambitious. The literature of health effects of ambient air pollutants, and of the related toxicology of industrial air pollutants, is extremely large. Working within the resource constraints of the overall appraisal of the status of indoor air pollution represented by this report, the review and documentation of health effects literature have proven to be selective rather than comprehensive. The hazard ranking of pollutants is a stubborn problem; it is approached but not resolved here.

8.1 SULFUR OXIDES

The principal sulfur oxide of interest in health effects studies has been sulfur dioxide (SO_2) but sulfate ion (SO_4), occurring as a component of sulfuric acid or its salts (sulfates), has also been extensively studied. Sulfur dioxide may be converted to sulfate ion (among other reactions) in chemical transformations which can take place in ambient air or on surfaces with which SO_2 comes in contact.

Researchers have found concentrations of SO_2 measured in indoor environments to be as high as 182 micrograms per cubic meter ($\mu g/m^3$) for a seasonal average [714] and over 1300 $\mu g/m^3$ for shorter periods [680] to cite only two values illustrated. Other values have been cited in Section 3.0. There is sufficient evidence to indicate the existence of an indoor SO_2 health effects problem, as the discussion which follows will show.

The considerable body of research reviewed as background for setting a National Ambient Air Quality Standard for SO_2 linked ambient concentrations with human effects ranging from reduced respiratory function to increased mortality from a variety of causes [607]. Research used as reference data in defining the SO_2 standards is summarized in Figure 25, taken from Stern et al. [607]. In Figure 25, the vertical scale at the left shows levels of ambient SO_2 concentration, over annual or 24-hour exposure periods, with which the corresponding health effects were associated. Because the adverse effects demonstrated in these studies were considered to represent the possible combined effects of sulfur oxides and particulate matter, Figure 25 also shows parenthetically the corresponding



[1] [illegible]

Figure 25. Reference data for sulfur oxides air quality criteria [207]

levels of smoke, coefficient of haze (Coh) or particulates measured in these studies. The studies reviewed in the preparation of the NAAQS criteria for SO_2 clearly indicated the hazard of both peak and long-term exposures to SO_2 when it is accompanied by elevated concentrations of particulate matter. However, the role of SO_2 alone in causing adverse effects at the NAAQS standard levels was not established.

The thresholds for irritant effects of SO_2 and sulfuric acid have been reported as 1600-2600 $\mu g/m^3$ and 600-850 $\mu g/m^3$, respectively by Bushtueva [642]. Administration of the two agents together produced these changes at a substantially lower threshold and Bushtueva considered the effects of the combination to be additive. Other studies reviewed by NAPCA [642] indicated that measurable respiratory function changes occurred at levels over 3000 $\mu g/m^3$ (1.2 ppm) for SO_2 and over 350 $\mu g/m^3$ for sulfuric acid mist, with associated exposure times of 30 minutes and 15 minutes, respectively. NAPCA considered that several important toxicological findings were derived from their review:

- Sulfuric acid aerosol is a considerably more potent irritant than SO_2, with effects more pronounced at particle sizes of 3 μ MMD or less and particle sizes less than 1 μ MMD were more effective at lower doses.

- Sulfuric acid mist is considerably more irritative than dry sulfate particles, indicating a more pronounced effect under conditions of high humidity.

- While SO_2 is absorbed in the upper respiratory passages and significant protection is provided by nose-breathing, 80 percent or more (by weight) of ambient suspended sulfates may be less than 2 μ MMD in diameter and penetrate deeply into the respiratory system.

- SO_2 inhibits respiratory clearance through reduced ciliary action and mucus removal, but at very high concentrations.

- The effects of sulfur oxides are, for the most part, related to irritation of the respiratory system.

The apparent minimal effects of SO_2 at usual ambient levels, the potency of sulfates and sulfuric acid, and the interaction of SO_2 and particulates relate to a number of unresolved issues.

In many epidemiological studies where SO_2 has shown significant association with health effects, correlations with particulate concentrations (variously measured as particulates, smoke or soiling) have been found. A number of investigations have reported a direct association between the concentration of suspended sulfates and the health effects [261, 597, 702, 721, 722, 723].

Studies by Sprey and Takacs [597] are interesting in that while there is no evidence of an increase in the incidence of carcinoma associated with exposure to concentrations of SO_2 alone, there was an increase in mortality from cancer of various types (respiratory, gastrointestinal, urologic) when elevated SO_2 concentrations were associated with elevated sulfate levels. Winklestein and Gay [699] found a graded positive association between suspended particulates and cirrhosis of the liver. Some correlation of SO_2 with mortality from respiratory and cardiovascular disease was present but strongest associations were found when elevated particulate or soiling levels were also present. The Sprey and Takacs [612] data revealed a positive correlation between mortality from arteriosclerotic heart disease, and neoplasms of the respiratory and gastrointestinal tracts, with increased sulfate levels. Winklestein et al. [702]

using sulfur oxides as the pollution measure, found a positive association between sulfation and chronic respiratory disease mortality.

While results of these studies were not consistent among age, sex, and socioeconomic groups, and other factors could have been involved (smoking habits were not measured), presumptive evidence is offered on several points:

1. Sulfates are involved in disease production beyond the cardio-pulmonary system, perhaps by reaction of SO_2 with metals or other particulates.
2. Although respiratory system cancer was found, primary bronchiogenic cancer was not. This may be due to the high solubility of the sulfates, and their rapid clearance to the blood, lymph, and gastrointestinal compartments. This is consistent with findings of the prominent effects of sulfur oxides occurring in the higher respiratory passages.
3. While SO_2 may serve as a proxy measure, direct sulfate measurement seems a more appropriate indicator of the potential hazard involved.

Early studies by Schimmel and Greenburg [545] and Buechley et al. [96] demonstrated an increased daily mortality in the New York metropolitan region with higher than usual SO_2 levels. However, Schimmel and Greenburg concluded that 80 percent of the excess was attributable to smoke and only 20 percent to SO_2. In a recent reevaluation of their data, Schimmel and Murawski [544] and Buechley [97] reached the conclusion that SO_2 was a proxy for some other factor. Schimmel and Murawski indicate the data suggest "that SO_2 is not only serving as an indicator of air quality but also that SO_2 is not an injurious pollutant, at least at the ambient levels encountered in New York City in the 1960's - namely, average levels of 0.2 ppm (525 $\mu g/m^3$) and peak levels of 0.6 ppm (1575 $\mu g/m^3$)" [544].

Finklea and his colleagues analyzed data from CHESS and presented evidence that adverse respiratory effects in the human are associated with sulfates, independent of SO_2 and other suspended particulates. In the case of asthma attacks, response to sulfate levels varied with temperature - the attack rate substantially increasing at lower sulfate levels when the temperature was above 50°F. For the series of responses analyzed in these studies, "best judgment" estimates of combined pollutant thresholds were made for adverse effects of long- and short-term exposures. These are included in Table 41. The authors consider that suspended sulfates have been identified as a pollutant of present concern but that there are many unresolved issues pertinent to establishing standards and control measures. These include better understanding of the environmental reactions and chemical makeup of sulfates and the biological response to sulfates.

In addition to the potentiating effect of SO_2 in air that also contains significant concentrations of particulates (sulfates, nitrates, heavy metals, etc.) there is evidence that other factors, such as the relative humidity, have an influence on the functional effects of SO_2 [150]. Guinea pigs were exposed to 1 ppm of sulfur dioxide and 1 $\mu g/m^3$ of sodium chloride aerosol. At low humidity (< 40 percent), the aerosol was a crystal and at high humidity (> 80 percent), a droplet. Increased flow resistance and decreased pulmonary compliance were only noted at high relative humidity.

TABLE 41. BEST JUDGMENT ESTIMATES OF POLLUTANT THRESHOLDS FOR SULFUR OXIDES AND SUSPENDED PARTICULATES

	SO_2	Total Suspended Particulates	Suspended Sulfates
Long-Term Effects (Annual Average, $\mu g/m^3$)			
• Increased prevalence of chronic bronchitis in adults	95	100	15
• Increased lower respiratory disease in children	95	102	13
• Increased frequency of acute respiratory disease in families	106	151	13
• Decreased lung function of children	200	100	13
Short-Term Effects (24-Hour, $\mu g/m^3$)			
• Aggravation of cardiopulmonary symptoms in elderly	≥ 365	80-100	8-10
• Aggravation of asthma	180-250	70	6-10

It is postulated that the highly soluble SO_2 was adsorbed into the droplets prior to inhalation, with the secondary formation of sulfurous acid and a lowering of the pH. It is not clear whether the described changes in respiratory mechanics were related to: the acidity; the (HSO_3^-); the sulfite ion ($SO_3^=$); or to transport of SO_2 to lower airways by the aerosol.

It is of interest at this point to note that the Threshold Limit Value (TLV) established for SO_2 by the American Conference of Governmental Industrial Hygienists [13] is at the high level of 5 parts per million (ppm), approximately 13,000 $\mu g/m^3$. Studies with human subjects cited in this report indicate the following effects of SO_2 with increasing concentration:

3-5 ppm - Noticable odor

8-12 ppm - Irritation of the mucous membranes, i.e., nose, eyes, e.c.

13 ppm - Increased airway resistance

150 ppm - Increased incidence of respiratory disease, hospitalization, deaths from all causes, etc.

These are considerably higher thresholds than those reported in the NAPCA data. TLV's are established for use in industrial contexts and are not necessarily applicable to the nonworkplace environment in which exposures may be of much greater duration and in which particularly susceptible populations of children, ill and elderly people may be found.

Wolff et al. [705] subjected healthy humans to concentrations of 5 ppm of SO_2 and found a slight decrease in the maximal mid-expiratory flow rate but no significant effect on muco-ciliary clearance.

The TLV of sulfuric acid is 1 mg/m^3 [14] since above this level it causes respiratory irritation and over prolonged periods, dental injury. In a study by Amdur et al. [11], in which normal human subjects were exposed to the inhalation of sulfuric acid mist for 5-15 minutes, concentrations below 1 mg/m^3 could not be detected by odor, taste, or irritation. A concentration of 3 mg/m^3 was noticed by most subjects, and 5 mg/m^3 resulted in irritation of the respiratory tract. Raule [511] noted that workers chronically exposed to H_2SO_4 may show lesions of the skin, tracheobronchitis, stomatitis, conjunctivitis and gastritis. There is also evidence that chronic exposure causes corrosion of dental enamel.

Concern with adverse effects of sulfate aerosols is strengthened by results of studies by Amdur and Corn [10] and Davies [150] which revealnd a significant increase in pulmonary airflow resistance in guinea pigs exposed to sulfuric acid droplets and particles of zinc ammonium sulfate, zinc sulfate, and ammonium sulfate.

In the light of the various reports of concentration levels at which sulfur dioxide is associated with adverse health effects, it is appropriate to recapitulate here some of the evidence for the existence of elevated SO_2 concentrations in indoor, nonworkplace environments. The highest 24-hour SO_2 concentrations found indoors have been on the order of 850 μg/m^3 [681] and 1300 μg/m^3 [359] found in Moscow and London, respectively. In Cincinnati indoor concentrations as high as 500 μg/m^3 were ruported [564]. In studies conducted in Hartford, Connecticut, seasonal averages of SO_2 concentrations were found as high as 102 μg/m^3 [714]. Information on indoor sulfate and sulfuric acid concentrations in nonindustrial environments is not yet available. Though SO_2 concentrations have been shown to be lower indoors than outdoors, the mechanism for SO_2 depletion may be a cause for concern since the process involves the oxidation of SO_2 to sulfates with potential hydration to form acid mists.

In summary, the combination of atmospheric sulfur oxide, its conversion products, and suspended particulates, appears to present a clear health hazard at commonly realized ambient levels, although the role of sulfur dioxide alone has not been clearly established. If recent work is correct, sulfates present a greater health hazard than SO_2. There is evidence that chronic exposure to sulfates may produce serious extrapulmonary effects, particularly neoplasms in the body systems involved in clearance.

Sulfates which tend toward micron and submicron sized aerosols may be important indoor pollutants. While SO_2 is reactive and may pose a minor indoor problem, it tends to disappear quite rapidly [144]. Suspended sulfates may remain at levels more equal to outside ambient levels and therefore present a more persistent hazard. Further research is indicated on the issues of chemical composition and concentration of indoor sulfates, and the human clearance of sulfates.

8.2 CARBON MONOXIDE

Carbon monoxide (CO) has been the most extensively studied of all pollutants in terms of toxicological aspects and this research seems to be continuing to a greater degree than for any other pollutant. The major aspect of the present interest is in effects on the cardiovascular system. Because the characteristics of CO health effects are so generally known, only a brief summary of salient points will be included here.

As previously noted in Section 3.0, while in some respects CO concentrations indoors are similar to those of SO_2, there is an important difference. CO is relatively unreactive and decays slowly, compared with SO_2. Since it is also generated indoors (from gas-fired appliances, leaky furnaces and chimneys, and from attached garages), it is an extremely important indoor pollutant.

The TLV for carbon monoxide is 50 ppm (approximately 55 mg/m^3) [14]. The inhalation of carbon monoxide, a colorless, odorless gas of specific gravity similar to that of air, causes asphyxiation (anoxia, hypoxia) by forming metastable chemical compounds, primarily with hemoglobin and secondarily, with other biochemical constituents which in a complex manner reduces the availability of oxygen for other cellular systems of the body. The resulting physiologic effect is similar to, but in some respects more serious than, a simple lack of oxygen caused by a rediced partial pressure in inspired air.

The equilibrium concuntration of carbon monoxide with the hemoglobin of the blood is substantially complete for individuals at work in 6 to 8 hours [13]. When the air contains 100 ppm of CO, the blood at equilibrium will contain 18-20 percent of carboxyhemoglobin (COHb); if air has 50 ppm CO, blood will have 8-10 percent COHb; for air of 25-30 ppm CO, there will be a 4-5 percent COHb.

The effect of carbon monoxide exposure on man is enhanced by factors such as heavy labor, high environmental temperature, and increasing altitude (above 2000 feet). Susceptibility is greatest in the aged, the very young, those with cardiac or chronic respiratory disease and with pregnancy [269]. However, some individuals, particularly cigarette smokers, have an increased tolerance to CO. The latter may tolerate COHb values of 5-10 percent (with its appreciable chemical effect) as compared to non-exposed adults.

The approximate relationships between ambient CO concentrations,* the percent of COHb in the blood, and the resultant symptoms, are as follows:

Atmospheric CO - ppm	COHb Concentrations - %	Principal Symptoms
50	7	Slight headache in some
100	12	Moderate headache and dizziness
250	25	Severe headache and dizziness
500	45	Nausea, vomiting, possible collapse
1000	60	Coma
10000	95	Death

An ad hoc committee, established in 1972 by the Bureau of Community Environmental Management, reviewed the effects of CO on human health with the specific objective of developing recommendations for residential standards. They concluded that continuous exposure should not exceed 15 ppm (resulting in about 2.6 percent COHb at equilibrium in nonsmokers). This level was considered to allow both for the higher CO concentration tolerance of smokers and the increased susceptibility of cardiac patients. Considering the ambient standard to be 9 ppm for 8 hours, indoor concentrations should not be allowed to raise the baseline air content by more than 6 ppm. For comparison, 15 ppm has been proposed as the short-term public limit by the National Academy of Sciences [447].

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* Occupational Health and Safety, International Labour Office, Geneva, Switzerland, 1972.

Stewart [610] recently reviewed evidence pertaining to the effects of low CO concentrations on man. CO is eliminated nearly completely by the lungs. In healthy, sedentary adults at sea level the biological half-life is 4 to 5 hours; this time increases with altitude. Increased blood flow, to compensate for oxygen reduction, is noted at 1-5 percent COHb and may be significant for those with substantially impaired cardiac reserve. Reduction in exercise tolerance is noted in normal individuals, and less exertion is required to produce anginal pain in cardiacs at 5-9 percent COHb. Above this level of COHb, definite symptoms and neurological changes are observed and increased mortality in those with severe cardiac disease is possible. For reference, exposure of a sedentary adult with normal physiology and under standard conditions of 50 ppm for 5 hours would raise COHb to about 5 percent.

A study of the possible correlation of ambient CO concentrations and the incidence of myocardial infarction and sudden death in Baltimore [361], did not support other evidence that CO exposure was a major factor. The risk of sudden death was higher in smokers than nonsmokers, and those who had formerly resided in high ambient CO areas had higher post-mortem COHb levels. The authors postulated that there may be a time lag between an increase in ambient CO concentrations and its deleterious effect in the human. Kuller et al. [361] did not find marked differences in post-mortem COHb levels in individuals with and without acute coronary lesions, nor were COHb levels related to the degree of coronary stenosis. Radford et al. [505] studied hospital admissions for chest pain and concluded that the clinical course and severity of infarction among smokers and nonsmokers

The special hazards of carbon monoxide in indoor environments are widely known. Studies have shown indoor concentrations of carbon monoxide at potentially hazardous levels to be a frequent occurrence. The impact of cigarette smoking on indoor CO levels has been often cited [88, 610, 531, 270, 40]. Internal combustion engines as sources of indoor CO produced symptoms of drowsiness, headache and nausea in school children which led teams of investigators to monitor for carbon monoxide in school buses and ice-skating rinks [335, 336]. Radford reported 1 percent of the sample of 302 old houses in Baltimore as having carbon monoxide levels greater than 50 ppm, attributed to faulty indoor combustion sources [504]. Biersteker and Yocom [69, 712] found similar faulty combustion sources in a small percent of the samples surveyed. These findings are of particular concern if extrapolated to a large population using stoves, heating systems and space heaters of which even a small percentage is faulty.

8.3 CARBON DIOXIDE

Carbon dioxide, while not normally considered a hazardous constituent of the air (with a normal ambient concentration above 325 ppm [557], under certain unusual circumstances can be present in the indoor environment in asphyxiating concentrations. There have been a number of instances reported, usually occupational in nature, where CO_2 has caused fatalities. The normal symptoms of excessive CO_2 exposure as reported by Hamilton and Hardy [266] are attributable to oxygen deprivation. These authors also state that "unconsciousness and death do not occur unless oxygen is as low as 5 percent - unless the victim makes strenuous exertion, in which case death may come while there is still 8 percent oxygen" [266]. Carbon dioxide has been reported to be a "weak narcotic at 10,000 ppm . . .

at 50,000 ppm, a 30-minute exposure produces signs of intoxication, and at 70,000 to 100,000 ppm, unconsciousness in a few minutes" [266]. The threshold limit value has been set at 5,000 ppm for an eight-hour exposure [14]. The personnel of a submarine experienced chronic fatigue when CO_2 levels reached 3 to 15 percent (30,000 to 150,000 ppm) for several weeks [374]. In the same report, LaVerne et al. state that CO_2 is easily "eliminated from the body and brain by reflex hyperventilation within seconds after treatment, thereby preventing cumulative toxic side effects."

Carbon dioxide has been used in varying concentrations for many different therapeutic reasons for almost 50 years. CO_2 is a cerebrovascular dilator and respiratory stimulant and has been used in the fields of pediatrics and geriatrics as well as for the treatment of narcotic addiction and alcoholism [374].

The normal ambient concentration of CO_2 is approximately 325 ppm. Ishido [326] has found indoor concentrations of CO_2 ranging from 1 to 10 times the outdoor concentration. Therefore the CO_2 comprised from 0.03 to 0.32 percent (300 to 3,200 ppm) of the indoor air [326]. Although these concentrations are not as high as the TLV, the potential exposure could be for longer periods of time than the 8 hours that the TLV's are based upon. Therefore, as LaVerne et al. stated "it appears that CO_2 inhalation, whether therapeutic or nontherapeutic can be as safe or as dangerous as the conditions created in each specific situation" [374].

8.4 NITROGEN OXIDES

The pollutants of concern among the nitrogen oxides are nitrogen dioxide (NO_2), nitric oxide (NO), nitric acid, and acid salts (nitrates). Nitric oxide (NO) peak ambient levels are not generally considered to present a direct health hazard; the greatest toxic potential of NO at these concentrations is related to its tendency to undergo oxidation to nitrogen dioxide [616]. The evidence for respiratory disease associated with NO_2 is cited below. Nitrogen oxide reaction products have been associated with equipment corrosion but biological effects are generally not well-researched. As contrasted with sulfates, nitrates appear to have a more uniform particle size distribution and the proportion available as respirable aerosols ($<3.5\mu$) may be smaller [606].

Few toxicological or epidemiological studies of atmospheric nitrogen oxides are available. Figure 27 from Stern et al. [607] indicates the parameters used to establish the National Ambient Air Quality Standards by NAPCA [646]. The original study reported reduced respiratory function in children, and increased respiratory illness among families, in the high NO_2 area [569]. Because the original aerometric data were considered unreliable, NO_2 data for the previous year were used in a subsequent analysis by Shy et al. [567] providing similar results at slightly different concentrations. Subsequent studies of the same Chattanooga areas were conducted by Pearlman et al. [482] and Chapman et al. [121]. Pearlman reported an increased incidence of bronchitis among school children in the defined high and intermediate NO_2 areas after two and three years of residence. No significant difference was found in the incidence of croup or pneumonia, or in reported hospitalization for lower respiratory tract

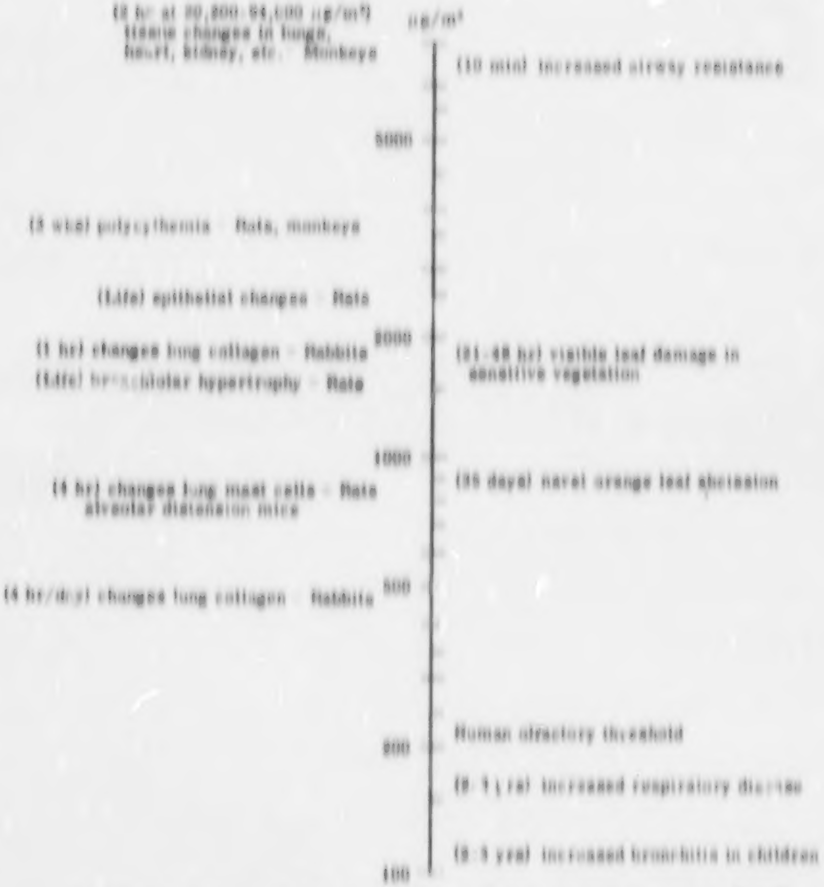

Figure 27. Reference data for nitrogen dioxide air quality effects [807].

illness. Chapman found no association between current or past pollution levels and the prevalence of chronic respiratory disease among parents of high school students residing in the three areas.

The original study of Shy and his associates was criticized by Warner and Stevens [677] because no attempt was made to control for acid mists, which were probably present in significant concentrations. Pearlman et al. [482] in their retrospective study found that for the intermediate and high NO_2 areas, suspended nitrates ranged from 2.6-5.8 $\mu g/m^3$ (24-hour mean over a six-month period). It is interesting to note that bronchitis prevalence was not related linearly to any of the pollutant measures, and that there could have been different contributions of pollutants in the various residential areas.

From a review of (unpublished) data produced in subsequent epidemiological studies of Chattanooga, Riggan [521] has proposed that "repeated short-term exposures of 228-815 $\mu g/m^3$ NO_2 may contribute to excess risk of acute respiratory disease in the absence of excessive long-term exposures." He points to the work of Coffin et al. [128] in which rats were challenged with bacilli after varying NO_2 exposures. This study showed that in short-term exposure to NO_2, the concentration employed has a much greater influence than the duration of exposure, for equivalent exposures (i.e., for equal products of concentration and time). Other work [129, 229] using an infectivity model in experimental animals, indicates that exposure to NO_2 and O_3 may decrease resistance to respiratory infection via destructive action on pulmonary alveolar macrophages - i.e., reduction in number, in phagocytic competence, in viability and enzymatic function. However, since the effect of a single dose of an oxidant on the macrophages is known to last approximately 24 hours (until they are replaced), the authors suggest that additional factors which enhance pulmonary infectivity are present - particularly with intermittent exposure to NO_2.

French [222] after reviewing published and unpublished data from the Chattanooga studies, concludes that the findings suggest:

> 1. Exposure to prolonged levels of nitrogen dioxide, ranging from 113 to 395 ug/m^3, in combination with short-term exposures of 301-1203 ug/m^3 may contribute to excess risk of acute respiratory disease and the residual effects from this exposure may last for as long as four years.
> 2. Repeated short-term exposures of 228 to 815 ug/m^3 may contribute to excess risk of acute respiratory disease in the absence of excessive long-term exposures.
> 3. Prior high short-term and long-term exposures to NO_2, coupled with continuous excessive short-term exposures, might trigger the onset of chronic respiratory disease symptoms.

Riggan [521] has developed a protocol for the prospective study of acute respiratory disease and its variation related to peak hourly and daily exposures to NO_2 and other pollutants. The study will be conducted in several locations in the Los Angeles basin to provide controls and a variety of pollutant combinations, including oxidants and sulfur oxides. Data collection is scheduled to begin in late 1976, with a preliminary report expected by February 1978.

The TLV established for NO_2 by the American Conference of Governmental Industrial Hygienists is 5 ppm (approximately 9 mg/m^3) [14].

This ceiling was to some extent established to minimize the risk of accelerating lung tumor development.

The TLV for nitric acid is 2 ppm (approximately 5 mg/m^3) [14]. In practice HNO$_3$ is usually found in conjunction with nitrogen dioxide. According to Fairhall, continued exposure to the vapor and mist of nitric acid may result in chronic bronchitis and more severe exposure, to chemical pneumonitis [199]. It may also erode the dental enamel [402].

Two recent studies which suggest a statistical association between mortality and exposure to nitrogen oxides have been identified. Sprey and Takacs [597] in analyzing data for 42 cities, found a strong association between NO$_2$ and median disease-specific mortality rates for hypertensive and arteriosclerotic heart disease, and for lung cancer. There was a fairly linear relationship for each cause of death for NO$_2$ levels, increasing from 0.3 to 0.8 ppm. Analysis of pooled variables and of independent age groups, subsequently showed arteriosclerotic heart disease to be associated with an interrelationship of NO$_2$ and ambient sulfate levels. (Because of the strong involvement of smoking in pulmonary carcinogenesis, discussion of air pollution and lung cancer is considered in more detail later.) In a similar type of investigation, Lave and Seskin [370] have reported an association between nitric oxide (NO) levels and daily mortality in Chicago (in Hershaft et al. [286]).

Much about the mechanisms and degree of nitrogen oxide effects is not well understood. Although apparently less acutely toxic than ozone, NO$_2$ is considered to have more similarities with O$_3$ than SO$_2$ in terms of biological actions. Aviado and Salem [47] point out that SO$_2$

and SO_3 are believed to exert their primary effects on the airways while NO_2 and O_3 exert their primary effects on pulmonary capillaries. A difference in solubility is possibly one reason, with the relatively insoluble NO_2 and O_3 able to penetrate deeply into the lung without appreciable loss in inspired concentration. Stockinger and Coffin [616] have listed a number of apparent analogies and dissimilarities in actions of NO_2 and O_3. Among differences cited are the high threshold of acute lung response, the relatively low toxicity, and the short-acting tolerance of NO_2. Most animal studies and observations on human responses to peak exposures have been at concentrations far exceeding typical ambient levels. It is understood that chamber experiments are now being conducted by EPA which will include NO_2 alone and in combinations with other major pollutants. With the limited epidemiological research, little information is available on sensitivity differentials. Presumably those groups mentioned for SO_2 would also be sensitive to NO_2. It has been reported that nitrogen oxides can result in increased methemoglobin so that anemics may be more susceptible. This effect may be due to the formation of organic nitrates (obtained by combining the NO_2 group with an organic radical) which are transformed into nitrates in the body. This promotes the formation of methemoglobin.[a]

Seinfeld [557] has stated that NO_2 is transformed in the lungs to nitrosamines, some of which are suspected human carcinogens. Johnson [339] has suggested that nitrous oxide (N_2O), if metabolized, could provide the nitrating source for nitrosamine formation in gastric juice or other acid substances in the body. He points out that there are many secondary amines in our diet (e.g., proline) and in tobacco smoke (e.g., pyrrolidine), of which some nitrosamine forms have been shown to be potent carcinogens in various animal systems. Johnson hypothesizes that this mechanism may be the causative agent in excess cancer mortality among anesthesiologists.

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[a] Occupational Health and Safety, International Labour Office, Geneva, Switzerland, 1972.

The hazard to human health from nitrogen oxides in indoor air may be assessed in the light of reported indoor concentrations. Peak one-hour average concentrations of NO_2 have been found in kitchens during gas appliance operations to range between 450 to 950 $\mu g/m^3$ [178, 184, 308]. Peak concentrations of NO_2 less than one hour in duration, have been reported as high as 1900 $\mu g/m^3$ (1 ppm) [178] and 2800 $\mu g/m^3$ (1.5 ppm) [184]. These values cannot be readily compared with the criteria which established the National Ambient Air Quality Standard (NAAQS) for NO_2 since the reference data were concerned with chronic respiratory illnesses. These indoor NO_2 data, however, may be compared with recent conclusions regarding short-term NO_2 exposures reported by Riggan [521] and French [222]. On reviewing the earlier NO_2 health effects criteria, principally the Chattanooga Study, the authors of those studies report that repeated short-term exposures to NO_2 contribute to an excess risk of acute respiratory disease in the absence of excessive long-term exposure. Riggan proposed a range of short-term exposures to NO_2 between 228 and 815 $\mu g/m^3$. The range of high one-hour average NO_2 concentrations reported in kitchens where gas-fired appliances are in operation, as summarized above, are within this range of potential risk to acute respiratory disease. Although a survey by the American Gas Institute does not lend support to this relationship, the AGI investigators did not monitor NO_2 in the homes where the survey was conducted.

Two studies have compared the incidence of reported respiratory illness in households cooking with gas and electricity. Eaton [179] found an association with the use of gas stoves but Keller et al. [349] could determine no significant difference among households. Further field studies to determine short-term NO_2 exposure and effects are required particularly in homes using gas-fired appliances. Additionally, nitric acid, nitrate, and nitrosamine concentrations should be monitored. Studies of the blood level concentrations of methemoglobin of residents of homes with and without gas-fired appliances is also indicated.

8.5 PHOTOCHEMICAL OXIDANTS

This section covers oxidants (excepting NO_2) that result from photochemical atmospheric reactions and their precursor gaseous hydrocarbons. The principal individual compounds in this class of primary interest as potential hazards to human health at ambient levels are:

- Ozone (O_3)
- Peroxyacetyl nitrates - peroxyacetyl nitrate (PAN) and peroxybenzoyl nitrate (PBzN)
- Aldehydes - formaldehyde (HCHO) and acrolein (CH_2CHCHO).

As previously described (Section 4) ozone and PAN are secondary pollutants in the ambient air, typically arising from interactions of automobile-generated hydrocarbons and NO_x emissions in the presence of sunlight. Ozone does not usually originate in significant quantities in indoor environments. Ozone and PAN are highly reactive and, like SO_2 do not persist in high concentrations indoors even when outdoor concentrations are high, because of rapid decay through absorption on indoor surfaces.

Many other organic conversion compounds are known or are hypothesized to exist in polluted air (e.g., organic peroxides, ketones) but not at concentrations for which effects on man have been documented. Similarly, many individual hydrocarbons have been identified in polluted air which are biologically active but human responses have not been found below concentrations of several hundred ppm. The precursor ambient gaseous hydrocarbons are considered important only as an index of potential photochemical conversion [644]. However, before these low-concentration pollutants are dismissed, two points concerning their toxicity should be made. First, the hazard from possible cumulative effects of repeated exposures at ambient levels is unknown. It has been demonstrated that repeated sublethal doses (one-fifth LD_{50}) of hydrogen peroxide can result in a cumulative effect and eventually death in experimental animals [618]. Second, many of these chemicals or their homologs are components of household and industrial products which are used in concentrations within the toxic range. Hazards from vapors and aerosols generated by the use of such agents will be taken up in subsequent sections.

Ozone has been found to be the major component of observed ambient levels of the photochemical oxidants and therefore is used as the standard in the measurement of total oxidants. For this reason, oxidants and ozone are frequently used interchangably in exposure-response studies, although varying concentrations of other oxidants with different biological actions may be present. The national standard for ambient ozone and oxidants is the same.

Figure 28, from Stern et al. [607], presents the data base used in development of air quality criteria for ozone and oxidants by NAPCA [644]. Because of its relative toxicity, the one-hour standard for oxidants is about one-fourth that of SO_2 and one-third of the California standard for NO_2 (0.25 ppm, one hour). The standard was based on level of oxidants associated with eye irritation. Few epidemiological studies were available and only a small number of them showed an association of deleterious health effects with oxidants: e.g., increased attacks in a small proportion of asthma patients and impairment of performance in student athletes (in the latter case involving oxidants and particulates). Sterling et al. [605] found a significant correlation between the concentration of ambient oxidants and hospital admissions for cardiovascular and respiratory conditions. However, they also noted similar strong associations for SO_2, NO_2, and particulate matter. Data analyzed by Wayne and Wehrle [679] showed no significant association between oxidant levels and school absenteeism due to respiratory illness.

According to Griswold et al. [255] ozone exposures for two hours at an average concentration of 1.5 ppm O_3 resulted in a 20 percent reduction of the timed vital capacity. In addition to its more serious effects, air concentrations of ozone in excess of a few tenths ppm causes headache and dryness of mucous membranes in exposed individuals [693]. After review

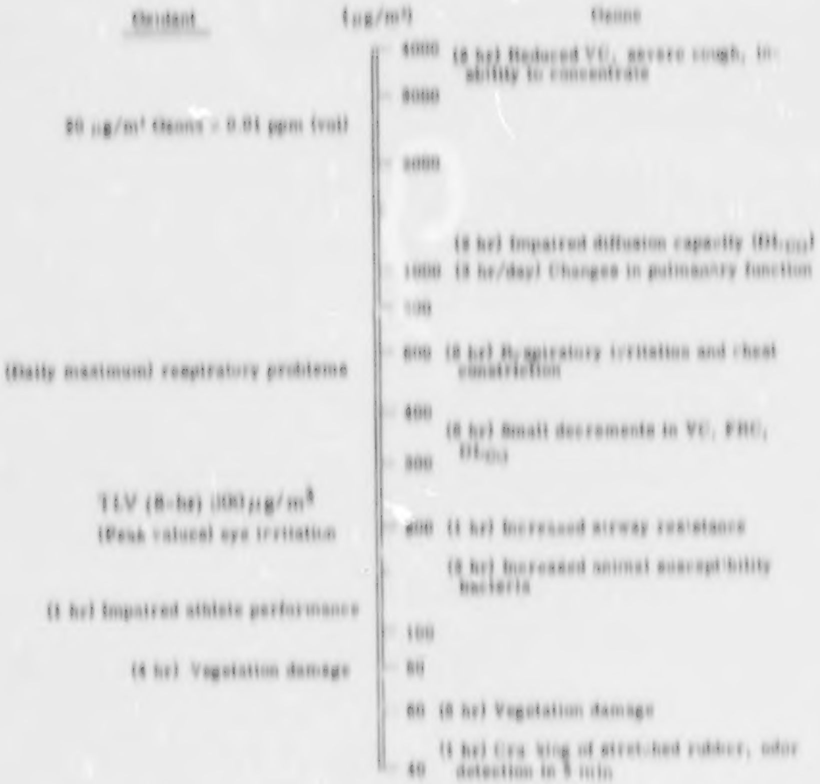
Oxidant
(µg/m³)
Ozone
4000
(2 hr) Reduced VC, severe cough, inability to concentrate
3000
20 µg/m³ Ozone = 0.01 ppm (vol)
2000
(2 hr) Impaired diffusion capacity (DL_CO)
1000
(3 hr/day) Changes in pulmonary function
800
600
(2 hr) Respiratory irritation and chest constriction
(Daily maximum) respiratory problems
400
(6 hr) Small decrements in VC, FRC, DL_CO
300
TLV (8-hr) 200 µg/m³
(Peak values) eye irritation
200
(1 hr) Increased airway resistance
(3 hr) Increased animal susceptibility bacteria
(1 hr) Impaired athlete performance
100
(4 hr) Vegetation damage
80
60
(8 hr) Vegetation damage
(1 hr) Cracking of stretched rubber, odor detection in 5 min
40

Figure 28. Air quality criteria for photochemical oxidants [307].

of the research and industrial health experience up to 1964 [615], it was pointed out that O_3 is radiomimetic and thus with continuous exposure (eight hours daily) to concentrations not acutely injurious per se, may be associated with premature aging and a shortened life span.

Hammer et al. [268] compared the daily percent of nursing students reporting each of several symptoms with the daily maximum concentration of oxidants. Patterns for several of the symptoms, particularly eye discomfort, conformed with oxidant levels. Further analysis of the symptom data [267] showed that incidence could not be attributed to carbon monoxide, nitrogen dioxide, or elevated temperature. The investigators developed oxidant thresholds for several symptoms: eye discomfort (0.15 ppm); cough (0.26 ppm); chest discomfort (0.30 ppm); and headache (0.50 ppm). A TLV for ozone established by the American Conference of Governmental Industrial Hygienists [14] is 0.1 ppm (approximately 200 $\mu g/m^3$).

Symptoms at various oxidant concentrations can be compared with results found in chamber studies. As a recent example, Hackney et al. [259] conducted a series of experiments with adult male volunteers who were subjected to short-duration (two and four hours) exposures to various levels of ozone. While the findings are too complex to cover fully, selected results are summarized in Table 42.

TABLE 43. EFFECTS OF CONTROLLED OZONE EXPOSURE ON ADULT MALES [289]

Group	O_3 (pphm)	Duration (Hours)	Respiratory Physiology	Symptoms	Blood Biochemistry
#1 - Normal	50-50*	4	Few changes	Few	NR+
#2 - Reactive	25 37 50	2 2 4→2	One measure Mild Marked	None Severe Marked	NR
#3 - Normal Reactive	50	2	Few or none Marked (2nd day)	Few or none Marked	 Oxidative changes Erythrocyte fragility
#4 - One Normal, Five Reactive	25**	2	Few or none	None	Few or none
#5 - Mixed	37	2	None important		Oxidative changes
One Reactive			Marked	Marked	Oxidative changes

* O_3, $O_3 + NO_2$ and $O_3 + NO_2 + CO$

** $O_3 + NO_2 + CO$

+ NR Not Reported

Reactive (sensitive) subjects, as defined by history or testing, developed such severe symptoms after exposure to 50 pphm for four hours, that subsequent exposure was shortened to two hours, even though normal subjects reported few symptoms. At 37 pphm (two hours), symptoms in some reactive subjects were more severe than at 50 pphm (two hours), but respiratory system changes were less marked. Normal subjects exhibited few important symptoms or signs at any level, for either time duration, or with various pollutant mixes. Oxidative blood changes were found in reactive subjects at 37 and 50 pphm, and increased erythrocyte fragility at 50 pphm. The decrements in pulmonary function at 37 pphm (two hours) are similar to those reported by Bates et al. [56] and Hazucha et al. [281].

The other agents have not been studied at ambient levels. PAN has been reported to approach eye irritation threshold at a concentration of 0.5 ppm in 15 minutes and an increased oxygen uptake (during exercise) resulted at a concentration of 0.3 ppm [616]. Formaldehyde is known to induce hypersensitivity and to depress ciliary activity. The irritation threshold of mucous membranes for formaldehyde has been reported to be between 0.01 and 1.0 ppm and for acrolein as low as 0.25 ppm. As these agents are not consistently proportional to ozone it may be suitable to investigate their irritant properties separately under ambient conditions. No information was identified on long-term, low concentration effects of these agents.

A survey of the origins and consequences of atmospheric pollution by vapor-phase organic pollutants published in 1976 by the National Research Council [460] notes that the photochemical reaction products of organic pollutants present potential hazards of mutagenicity as well as the unfavorable health effects of ozone, lachrymators such as PAN and PBzN, and the aldehydes.

The hazard to human health from ozone in indoor concentrations may be assessed by comparing the results of these health effects studies to the levels of ozone which researchers have reported inside buildings. Indoor one hour ozone and oxidant concentrations have been reported to range as high as 300 to 500 $\mu g/m^3$ (14-16 pphm) in a surgical intensive care unit. The buildings where ozone or oxidant values were reported in this range were reasonably well ventilated. Inside ozone or oxidant values in residential buildings and schools were between 50 to 80 percent of those found outdoors [561, 626, 627]. In comparison with ozone criteria associated with adverse health effects (Figure 28), these values are in excess of those associated with eye irritation and increased airway resistance. However, the relative indoor-outdoor relationship indicates that significant protection from ambient levels may be achieved in air conditioned buildings.

Further investigation of the effects of ozone and other oxidants seem indicated including:

- The synergistic health effects of oxidants in the presence of particulates, sulfates, and nitrates
- The long-term effects on those chronically exposed to typical ambient levels.

8.6 ORGANIC POLLUTANTS

The term "organic pollutants" as used here refers principally to the diverse class of manufactured organic chemicals which may enter the air (1) in the vapor or liquid phase of aerosol spray operation, (2) through vaporization from the surface of liquid solvents, fuels, household cleaners and similar products, or (3) as a residual dust from pesticide use. Organic pollutants also include complex aldehydes which may arise from cooking operations. The term "organic pollutants" in this context does not include the photochemical oxidants which have been considered earlier, nor does it include the biological and allergenic materials which have not been examined in this report.

The nonphotochemical organic air pollutants do not fit neatly into categories of gases and particulates. They may occur in both phases, even simultaneously in the case of aerosol sprays. As particulates they may be in the form of liquid droplets in an aerosol or as solid particles for some pesticides.

Organics are contained in a wide variety of products used in homes, offices, and schools. They may be present in either the active ingredients or the propellants of packaged aerosol sprays, as well as being used directly in liquid applications. Many of them contain chlorine, bromine, or fluorine, forming a general class known as halogenated hydrocarbons. These substances in general can cause liver and respiratory system pathology and are neurotoxic. Several (carbon tetrachloride, trichlorethylene, chloroform, vinyl chloride) have produced cancer in animals. The degree of toxicity of the organics varies considerably. The discussion of health effects of organic pollutants may be somewhat arbitrarily considered under headings of solvents and fuels, aerosol propellants, and pesticides and combinations of pollutants.

8.6.1 Solvents and Fuels

One of the major sources of exposure to toxic chemicals in indoor spaces is through the endless variety of products used as fuels, cleaners, paint and paint products, laundry products and hobby materials. Other than their use as fuels (propane, butane, gasoline, kerosine, etc.), most of these chemicals are used directly as solvents (degreasers, paint removers) or are solvent components of compounds (paint thinners, kitchen and bathroom cleaners, plastic and rubber cements). Many are in gaseous form; many others volatize readily or are used as sprays. Little information pertinent to evaluation of human hazards in nonindustrial exposure situations are available, so that we must turn to studies made for workplace settings.

Table 43 lists health-related information for a number of chemicals commonly found in domestic products to illustrate the variation in type, toxicity and dose-response data. Threshold Limit Values (TLV's) given are recommendations for 8-hour average time weighted exposure for healthy adults assuming a 40-hour work week. Therefore, the TLV's are only crude proxy guidelines at best for household exposures and perhaps several times higher than a "safe" level, particularly when children and more susceptible persons are involved. The exposure-response data given is the information available concerning the lowest concentrations at which human effects were observed. Most of these studies are on short-term exposures and acute effects. Data on long-term exposure is seldom found.

Many of the chemicals in this section fall into a number of groups which have common exposure characteristics and toxic properties. The review that follows was drawn primarily from Hamilton and Hardy [266].

Saturated Aliphatic Hydrocarbons - Of interest in this group are the gases methane, propane and butane, and liquids from pentanes (C_5) through C_{16} compounds. Methane, the principal component of natural gas, is biologically inert. In general the series from propane (C_3) through the octanes (C_8) show increasingly strong narcotic properties, although the thresholds are very high. Sources of vapors from compounds containing liquid hydrocarbons in the series from pentane through octane

TABLE 41. ILLUSTRATIVE HEALTH INFORMATION ON SOME HOUSEHOLD SOLVENTS AND CLEANERS

Compound	Use	TLV*	Exposure-Response Data*
Methylene chloride	Paint remover	200 ppm (720 mg/m^3)	100-200 ppm per day results in increment of 4.5 percent COHb. Narcosis above 4,000 ppm. Brain damage reported from repeated peaks above 500 ppm.
Perchloroethylene	Cleaning fluid	100 ppm (670 mg/m^3)	100 ppm for 7 hours produced narcotic effect, headache, mild eye and respiratory irritation. Marked narcotic effect above 200 ppm for 3 hours.
VM&P Naphtha	Paint thinner	300 ppm (900 mg/m^3)	Multiple hydrocarbon content (TLV based on toluene, xylene).
Benzol (benzene) Toluol (toluene) Xylol (xylene)	Lacquer and cement solvents	10 ppm (30 mg/m^3)-Skin	Myelotoxicant. Skin absorption can produce chronic poisoning. Headache, nausea, narcosis above 200 ppm. May contain benzene 200 ppm irritating. GI, neurological and vascular effects reported in workers. May contain 6-15 percent ethyl benzene.
Methanol	Shellac and varnish thinner	200 ppm (260 mg/m^3)-Skin	No worker injury at average 160-780 ppm. Repeated exposure above 1,000 ppm may result in cumulative body concentration.
Acetone	Lacquer solvent	1000 ppm (2400 mg/m^3)	Minor eye and nose irritation above 2500 ppm.
Ethyl ether	Lacquer, wax, plastic solvent	400 ppm (1200 mg/m^3)	Nasal irritation above 200 ppm. No worker injury demonstrated from regular exposure of 300-1000 ppm. Chronic effects noted after long-term exposure.
Sodium hydroxide	Drain cleaner	2 mg/m^3	Upper respiratory irritant at 2 mg/m^3.
Ammonia	Window cleaner	25 ppm (18 mg/m^3)	Rat ciliary motion stopped at 3 ppm. Detection at 1-5 ppm. Eye and nasal irritation at 20-25 ppm.
Turpentine	Pnt. thg	100 ppm (560 mg/m^3)	Respiratory irritation at 75 ppm. Marked irritation and nausea occur above 750 ppm for several hours.

* TLV's and Response Data from Documentation of the Threshold Limit Values [16].

are mixtures such as petroleum ether, benzine, petroleum naphtha, gasoline, mineral spirits, Stoddard solvent and varsol - which are commonly found in household use. The vapors are moderately irritating and have narcotic effects typical of heptane or octane. However, these mixtures may contain other chemicals such as benzene which are of much greater significance toxicologically.

Aromatic Hydrocarbons - The important chemicals here are benzene, toluene and xylene, which are used as plastic and rubber solvents. Many hydrocarbon mixtures, and in particular coal- and petroleum-derived solvents, may contain unknown quantities of benzene. Besides the central nervous system depression usual to hydrocarbons, benzene exposure can result in chronic poisoning with insidious onset, resulting in aplastic anemia and possibly leukemia. Toluene and the xylenes are less toxic and similar in their effects, which are primarily narcotic. Lethal cardiac arrhythmias have resulted in "glue sniffers." There is some evidence that toluene also may be a myelotoxicant after chronic exposure but a causal association has not been established.

Chlorinated Hydrocarbons - This group includes most of the solvents routinely encountered in cleaning and painting products. Toxic levels vary considerably. Two of these agents, carbon tetrachloride and chloroform, have been identified as carcinogens in laboratory animals. Toxic manifestations reported for the various chlorinated hydrocarbons have included eye and respiratory irritation, neurasthenia, cardiac irregularities, and liver damage. The extreme volatility of these compounds permits rapid achievement of significant concentrations within a short time. Absorbed dose varies with metabolism. For example, most, like tetrachloroethylene, are exhaled unchanged. Methylene chloride however is almost completely metabolized to carbon monoxide, a unique and dangerous characteristic [616].

Other Solvent Compounds - Other chemicals of interest are the alcohols, ketones and ethers, esters, acids and caustics. *Methanol* is a component of lacquer thinners and canned heating preparations (sterno). Eye and respiratory irritation may result from exposure to vapors but systemic intoxication is unlikely without accidental ingestion. *Ketones and ethers* are common lacquer solvents. Acetone is the most frequently encountered. Others of this group are more irritating, but severe complaints have occurred only a very high occupational levels. Bis-chloromethylether (BCME) has been established as a human carcinogen but is unlikely to be found outside of industrial settings or laboratories. *Aliphatic esters*, primarily ethyl acetate and butyl acetate, are used as lacquer thinners. Vapors are irritative but other significant toxicological effects have not been established. Several types of *acids and caustics* may be found in the home: sulfuric, nitric and hydrochloric acids, sodium hydroxide, ammonia. Except for nitrous fumes from exposure of nitric acid to air, or deliberate creation of aerosols through spraying, most of these products are likely to produce only minor irritative effects in their usual applications.

In recent years the dose-response characteristics of many common solvents have been undergoing reevaluation, using improved biological monitoring techniques [649]. It has been found that measures of exhaled breath concentration and metabolites in blood and urine have correlated much better with biological response tests than air concentrations. These investigations have led to establishment of standards on a firm metabolic basis.

Stewart [610] has confirmed the metabolism of methylene chloride to carbon monoxide and he has developed the correlation of ambient concentrations of CH_2Cl_2 with COHb levels in those exposed. Haise [265] indicated that the Wisconsin group has now tested 10 solvents, and they and others have found that only the dihalomethanes are CO converters. In testing the usual standard levels with human volunteers, they have not identified any factor which would indicate a need to change the recommendations for acceptable concentrations.

8.6.2 Aerosol Propellants

The three essential components of aerosol sprays are the propellant, the solvent, and the active ingredient. Each might prove hazardous to health. The most common propellants are fluorochlorohydrocarbons bearing the trade name Freon.* Freon 12, the most common of the group, is a gas at room temperature, is relatively inert and has a high vapor pressure that provides the propellant force. We know little concerning the range of exposure to aerosol sprays that might occur with their use in relatively confined (indoor) space [219]. The use of these propellants varies from hand nebulizers (i.e., by asthmatics), to hair sprays, to other purposes.

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* Freon is a trademark of the E.I. DuPont de Nemours & Co.

Fluorocarbons in high concentrations have been reported to affect both the respiratory and cardiovascular systems. Taylor and Harris [623] noted that a mixture of Freon 12 and Freon 114 induced sinus brachycardia and atroventricular block in experimental animals. The arrhythmias were more readily elicited and more severe if anoxemia was present. Some critics maintain that these effects are noted only when unrealistically high concentrations of fluorocarbons and other substances are combined [125]. Harris and Kilen [274] in further studies reported that Freon 12 affected the contractility of myocardial muscle fibers. An increase in mortality from asthma in children and young adults in England and Wales during the last decade has been attributed to the introduction of hand nebulizers [219]. One hypothesis is that the hypoxemia (and hypercarboxemia) of the underlying asthma, in combination with the inhaled fluorocarbon and adrenogenic drugs, led to fatal cardiac arrhythmias. Trochinowitz et al. [623] found that industrial halocarbons posed no greater risk in persons who had recovered from myocardial infarcts than in normal individuals.

Morgan et al. [435] used radioactive tracer techniques to study retention of Freon in human volunteers. Mean retentions of these substances were:

- Freon 11 - 23.0 percent (± 2.2)
- Freon 12 - 10.3 percent (± 2.2)

- Freon 113 - 19.8 percent (± 0.9)
- Freon 114 - 12.3 percent (± 4.1)

indicating that much of the vapur was exhaled without being absorbed. After 30 minutes the fraction retained in the lungs ranged from 10 percent for Freon 114 to 23 percent for Freon 11. Only a small fraction was presunt in the blood at 5 minutes. The authors concluded that because of low liquid solubility, absorption is quite slow and more than half the material is exhaled immediately.

Foltz and Fuerst [216] conducted mutation studies with Drosophila Melanogaster exposed to four fluorinated hydrocarbons. They found significantly increased mutation rates in the F2 generation, including two tumors not previously reported in deviant genotypes. The contribution of anoxia to mutations was not determined. Vozovaya [672] used dichloroethane in mutagenic and hetrogenic studies of rats. Although concentrations did not produce observable toxicity, reduced fertility, reduced birth-weight and an increased still-birth rate were detected. Increased perinatal mortality was seen in second generation litters from exposed males.

8.6.3 Pesticides

The term pesticide is used here in a generic manner and includes the wide variety of chemicals used as insecticides, miticides, fungicides, rodenticides, and herbicides. Many of these chemicals can be obtained in a number of forms (powders, dusts, liquids) for application and used for multiple purposes. Frequently they are combined in proprietary preparations.

When considering the relative toxicity of each chemical, one must review the following points:*

- The lethal dose in animals
- The method of use (solid, liquid spray, dust)
- The route of human absorption (ingestion, skin absorption, inhalation)
- The vehicle ir which the prsticide is applied - the diluent itself may be toxic or may influence the rate of absorption
- The formulation - many pesticides contain nonpesticide ingredients which may enhance toxicity, combinations of pesticides may act in synergistic or antagonistic fashion relative to human toxicity.

The individual chemicals and combinations are far too numerous to discuss separately here but important characteristics of each class can be described.

The following summary of pertinent aspects for major classes of pesticides is drawn from Hamilton and Hardy [266].

Organophosphorous Compounds - The mechanism of toxic action of these compounds is based on their inactivation of acethylcholinesterase. The natural substrate (AcCH) of this enzyme is a primary neurohumoral transmitter substance. Because of certain structural similarities, the organophosphorous compounds undergo changes analogous to the natural substrate. However, the bond to the enzyme is abnormally stable so that the phosphorylated enzyme loses its normal function as a AcCH esterase, causing first increased function and finally decreased function, with greater AcCH accumulation.

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* Occupational Health and Safety, International Labour Office, Geneva, Switzerland, 1972.

The consequences are primarily disturbances of the central and autonomic nervous systems. Systemic responses produce initial symptoms such as anorexia, nausea and sweating. Eventually the respiratory muscles may be impaired. Studies of workers with chronic exposures have shown neurological deficits (memory defects, delayed reaction times) without obvious clinical signs of intoxication.

There is wide variation in mammalian toxicity shown by this group. Certain sulfur-substituted compounds require metabolic oxidation before toxicity develops (e.g., parathion), while others (e.g., TEPP, phosdrin, DDVP) do not require such modification and are direct inhibitors of AcCH. The latter generally are more toxic and show more rapid onset of systemic symptoms. Recent evidence [706] indicates that parathion and related compounds are more toxic when inhaled than by skin absorption. Also, the toxicity of parathion may be potentiated by ultraviolet and visible irradiation.

Chlorinated Hydrocarbon Insecticides - The mechanism of action in mammals or insects is not clearly understood. It is apparent that these materials are neurological poisons, and severity of symptoms appears to be directly related to the concentration in nervous tissues. Signs of central nervous system stimulation from slight exposures include headache, anorexia, nausea and irritability. Increasing exposure produces weakness paresthesias, tremors and muscle fibrillation. Seizures or coma may occur after high levels of absorption. Long-term, low-level exposures produce the clinical picture of acute response to intense single exposures after sufficient dose.

Compounds in this category can be absorbed through ingestion, through inhalation, and most through the skin. Dieldrin can be absorbed through the skin in a dry state, the others must be in solution. There are two particular health concerns with the chlorinated hydrocarbons. First, the material absorbed is stored in fatty tissue. It has been noted that the total amount stored in the fat of an experimental animal may be greater than the amount necessary for a single fatal dose. Although the stored material is probably biologically inactive, there is a question of the potential danger from release of the pesticide during periods of rapid weight loss. The second concern is the carcinogenetic potential of these compounds. Those identified so far as possible human carcinogens are aldrin, dieldrin and DDT. Because of these concerns, use of DDT has been banned in the U.S. and others are being withdrawn or limited in application. However, pesticides in the same chemical and toxicity categories remain in common use.

Persistence of the chlorinated hydrocarbons over time at effective levels aids their insecticidal properties but consequently poses a health hazard. Davies and his associates [151] studied DDT concentrations in an area where no aerial spraying had been done but where this insecticide was used extensively for domestic pests. They concluded that contamination of house dust was primarily responsible for the human serum residues found. Comparison of exterior soil and interior dust revealed contrasts in concentrations of 8.4 ppm outdoors and 129.1 ppm inside.

Inhalation of contaminated house dust may be one important source of uptake. Another source consists of the continuous vapors from sprayed insecticides or from solid forms such as Shell's No-Pest Strip (DDVP). Although the long-term consequences of such exposures have not been demonstrated as adverse, many scientists feel that the use of these products is imprudent. Although we have not obtained the detailed results, we understand that Savage has recently shown that heavy application of chlordane and similar chemicals for termite control can result in significant levels inside the home five years after the spraying. Thus substantial indoor exposure does not necessarily depend on direct household use of these pollutants.

Other Pesticide Compounds - The two categories described above probably are the most important in terms of potential health consequences. However, many other toxic compounds are in general use. Carbamates are growing more popular because of their effectiveness and relatively low order of mamalian toxicity. These chemicals are also cholinesterase inhibitors but the reaction is rapidly reversible when exposure ceases. Most aerosol "bombs" for home use contain esters of the biological pyrethrum. Other biological derivatives used are rotenone and nicotine. Pyrethrum and rotenone may cause skin sensitivation but systemic intoxication is not of concern. Nicotine however, is a potent neurotoxic agent which may be absorbed from skin, lungs or GI tract.

There are a considerable number of other chemicals which may be of importance as indoor pollutants because of applications on foliage and soil around indoor spaces. These include those for mites and other plant pests, fungicides, soil fumigants, and herbicides. Among those of note are:

Chlorbenzilate and Chlorbenside - These miticides resemble the chlorinated hydrocarbons and have similar effects.

Dithiocarbamates - Foliage fungicidal sprays which may cause eye and nasal irritation but are not considered to have important systemic toxicity.

Organomercury compounds - Aryl mercury compounds, the less toxic of this group, are more likely to be used as domestic fungicides. Mercury is a neurotoxic poison and can cause active dermatitis.

Phthalimides - Frequently found in home garden fungicides, they have not been shown to be a significant hazard.

Dinitrophenols - These are used in different formulations as herbicides, fungicides, miticides and insecticides. Action in man is based upon interference with temperature control mechanisms. Members of this group used for domestic applications are less toxic systemically but are eye and airway irritants.

Chlorphenoxy group - This group includes the well-known herbicides 2,4-D and 2,4,5-T. Skin absorption is slight and toxicity by oral or inhalation routes has not been a reported health problem.

General statements in attempting to evaluate pesticides as an indoor pollutant hazard are made difficult by the variety of formulations, biological actions and toxicity levels associated with the many products in use. Some of the aspects pertinent to exposure have been pointed out: persistence in house dust, vaporization, transformation through oxidation to a more toxic substance. To illustrate the diversity of pesticides, Table 44 summarizes some relevant data on selected chemicals.

TABLE 44. ILLUSTRATIVE SUMMARY INFORMATION ON SELECTED PESTICIDES

Compound	Use	TLV	Toxicity	Exposure-Response Data
Organophosphorus Parathion	Plant pests 15 percent aerosol, 2 percent dust [379]	0.1 mg/m³ (skin)	LD50 rats oral 3-13 mg/kg, dermal 6-21 mg/kg [379]	Fluctuating plasma 0.1-0.8 mg/m³ decreased enzyme activity [11] Inhalation toxicity greater than by skin absorption [11] Aerosols (mists, dust) highly hazardous [379]
Azinphos-methyl (Guthion)		0.2 mg/m³ (skin)	LD50 rats oral 11-18 mg/kg, dermal 220 mg/kg [379]	1.7 mg/m³ air equivalent (in dietary intake) produced no effect in man Relatively low dermal toxicity probably accounts for good safety record
Dichlorvos (DDVP, Vapona)	Household insects Aerosols, vaporizers	1.0 mg/m³ (skin)	LD50 rats oral 56-80 mg/kg, dermal 75-107 mg/kg [379]	0.15-0.33 mg/m³ for 30 minutes/hour for 10 hours over 15 days produced no enzyme depression [11]. 1 mg/m³ for 7-8 hours produced 20-25 percent plasma cholinesterase depression [11]
Malathion	Plant pests, household insects Solutions, dusts	10 mg/m³ (skin)	LD50 rats oral 1000-1375 mg/kg dermal 4000 mg/kg [379]	84.8 mg/m³ 1 hour for 42 days produced no adverse symptoms or significant changes. Increases irritation of nose and eyes [11]
Chlorinated Hydrocarbons Lindane (BHC)	Household insects, termites. Many formulations	0.5 mg/m³ (skin)	LD50 rats oral 88-91 mg/kg, dermal 900-1000 mg/kg [379]	Gamma isomer (Lindane) of BHC exhibits greatest toxicity but relatively rapid excretion. Contact dermatitis reported from vapor. Toxicity varies among species [379]. 0.19 mg/m³ continuous for 600 days with no effects in rats. 0.1 mg/m³ average long-term repeated exposure produced minimal pathology in rats. Technical BHC produced symptoms in mice at oral doses of lindane tolerated for 14 days [11]
Dieldrin	Household insects (Dieldrin) 0.5 percent solutions, low percentage dusts	0.25 mg/m³ (skin)	LD50 rats oral 46 mg/kg, dermal 60-90 mg/kg [379]	Metabolite of aldrin with similar characteristics. Undissolved dieldrin readily absorbed through skin, in contrast with DDT. Repeated exposure has cumulative toxicity and residual hormone-induced liver may persist [379]. Air dose established on basis of analogy to lindane [11]
Heptachlor	Household insects Granulates (25 percent), 2.5 percent dusts	0.5 mg/m³ (skin)	LD50 rats oral 100-162 mg/kg, dermal 195-250 mg/kg [379]	Action similar to aldrin, chlordane. Dermal toxicity to man estimated 45 gm single dose, 1.5 gm/day multiple exposure [11]
Methoxychlor	Household insects Many formulations	10 mg/m³ (skin)	LD50 rats oral and dermal, 6000 mg/kg [379]	200 mg/man/day dietary dose over 2 years produced no symptoms; 100 mg/man/day produced no tissue changes [11]. No inhalation data found
Carbamates Carbaryl (Sevin)	Plant pests 10 percent dusts, 80 percent liquid sprays	5 mg/m³	LD50 rats oral 850 mg/kg, dermal 4000 mg/kg [379]	Dietary levels in rats of 200 mg/kg/day without significant effect [380]. Compound quickly metabolized. Inhalation of human equivalent of 100 mg/day (10 mg/m³) in rats produced no gross visible injury. No data available for TLV [11]
Biologicals Pyrethrum (Pyrethrin)	Household insects Aerosols	5 mg/m³	LD50 rats oral 820 mg/kg [11]	15 mg/m³ per 30 minutes for 31 days produced only slight lung irritation in rats, dogs. No data available for TLV [11]
Dithiocarbamates Thiram	Plant pests Sprays	5 mg/m³	LD50 rats oral 1300 mg/kg [11]	Rats survived dosed with aerosolized 500 mg/m³ for 4 hours. Similar effects as carbamates, but more toxic. Little experience data. No data available for TLV [11]
Phenols Pentachlorophenol	Insecticide, fungicide, herbicide	0.5 mg/m³	Lethal I.V. dose to rabbits 22 mg/kg [11]	Irritation of nose at 0.3 mg/m³, marked irritation to nose and eyes above 1 mg/m³. Skin absorption major factor in reported serious effects [11]
Dinitro-o-Cresol (DNOC)	Pesticide, fungicide, herbicide	0.2 mg/m³ (skin)	LD50 rats 31 mg/kg [11]	Humans non-fatal intoxication above 0.3 mg/m³. Cumulative blood levels and toxic effects after repeated exposures [11]
Phthalimides Captan	Protective fungicide	5 mg/m³	LD50 rats oral 12.5 g/kg [11]	Low order acute toxicity but much higher chronic toxicity. 8000 mg/kg in [illegible] animals caused slight skin irritation. Acceptable daily intake for man estimated at 0.1 mg/kg/day. No data available for TLV [11]
Mercurials Alkyl Mercury	Fungicide	0.01 mg/m³ (skin)	10 mg/m³ lethal to mice	0.01-0.1 mg/m³ with higher peaks did not reveal evident symptoms of Hg poisoning. However, [illegible] compounds considered more toxic; TLV is 0.05 for other non-alkyl Hg compounds [11]
Arsenic	Plant pests	0.25 mg/m³ as As		TLV based on potential toxicity as dust contribution to occupational dermatitis. No inhalation data on As in dusts or includes spray [11]

8.7 PARTICULATES

Particulates are a subset of the larger class of aerosols, an aerosol being defined as a colloid system in which liquid or solid particles are dispersed in a continuous gaseous medium. Aerosols are ubiquitous in man's environment. They include primary particulate matter (pollen, dust, soot, fibers) emitted from natural or anthropogenic sources and suspended in ambient air, and they include secondary particulate matter (sulfates, nitrates, some hydrocarbons) which are formed in the atmosphere by gaseous reactions involving SO_2, NO_x and oxidants. Aerosols also include the large class of diverse materials packaged under pressure to be dispersed by a gaseous propellant (a class including deodorants, paints, hair sprays, etc.). Particle sizes of aerosols range from that of aggregations of a few molecules to visible dust and vapor.

The mix in these aerosols includes substances that are inert and others that are biochemically and biologically active. The gas components of aerosols range from those harmless to man in appreciable quantities to those extremely hazardous in relatively small concentrations. These chemical substances may not be detectable by any of the senses, may not produce significant early physiological effects (to warn of their presence before serious injury) and may not produce clinically recognizable pathology until many years after exposure. These facts, and the continuing introduction of new materials in our environment from changing technology, make evaluation of hazards extremely difficult and complex.

Brain and Valberg [79] have described the results of studies on respiratory aerosol retention, employing a model developed by a Task Group of the International Commission on Radiological Protection. Three distinct physical mechanisms are involved in deposition of particles: inertial impaction, sedimentation, and Brownian motion. The relative significance of these mechanisms depends on the anatomy of the respiratory tract, the effective aerodynamic diameters of the particles, and the pattern of breathing. The important anatomic pulmonary changes, such as diminished lung volume, are associated with aging and with various types of respiratory disease. Particle aerodynamic characteristics are a function of particle size, shape, and density. Breathing patterns change as a result of exertion, existing pulmonary disease and various biochemical stimuli.

Clearance of inspired substances is a complex process including direct expiration, transport by cilia and mucus to the pharynx where the material is swallowed, and absorption into the blood stream. Metabolism and excretion from the blood, gastrointestinal and urinary tract are related to the chemical properties of the individual substances involved. The inspired material may physically or biochemically affect clearance mechanisms, and metabolites may induce pathology before clearance or be deposited in body tissues where the potential for long-term action is realized. Results from the model developed by the ICRP demonstrated that variations in effective particle size and solubility can greatly alter retention and exposure in some respiratory compartments [79].

Another recent study deserving citation here is an analysis of trace element retention in the human respiratory system using proton-induced X-ray emission techniques. Desaedeleer and Winchester [161] measured the respiratory retention of lead halide and chalk dust sized by cascade impactor with stages ranging from 0.25-4 μm. For both substances, minimum deposition was well under 50 percent with particles in the region of 0.5 μm diameter, and deposition was well over 50 percent for both smaller and larger particles. Retention results were consistent with those found using the ICRP model and with those reported by other investigators: minimal retention of particles in a size range of about 0.3-1.0 μm, with larger particles captured in the naso-pharynx compartment and smaller particles lodging primarily in the pulmonary compartment.

The health hazards for several classes of particulates and other aerosols are discussed below, grouped under the following headings:

- Total suspended particulates
- Tobacco smoke
- Trace metals and minerals.

These categories do not embrace the whole range of possible aerosols - biological pathogens and allergens have been excluded, for instance, because of time constraints in the literature review - and they are not mutually exclusive categories. They have been selected as areas of special interest to researchers.

The organic compounds which enter the indoor air as components of aerosol sprays will not be discussed under this section. They appear in Section 8.6.

8.7.1 Total Suspended Particulates

The standard method of measuring the particulate content of outdoor air has been to weigh the total amount of particulate matter of all kinds retained on a filter paper through which ambient air has been forced by a high volume air pump for a 24-hour period. The only characteristic of the particulate matter so identified is its weight per unit volume of air passed through the filter. The wide availability of these measurements of total suspended particulate (TSP), usually expressed in terms of 24-hour average ambient concentrations in micrograms per cubic meter, has led to the use of this measure of particulate concentration in epidemiological studies. A cruder measure of TSP, the soiling index, has also been used.

Sized analyses of ambient particulate matter, which separate particles into size ranges, are available for research studies of the smaller, respirable fractions of particulate. This type of particulate analysis is not routinely available from air quality monitoring systems established by states and cities. It is usually available only in special research contexts, such as EPA's Community Health Air Monitoring Program and other pollutant monitoring projects especially established for health studies.

Total suspended ambient particulates as a group have been implicated in a variety of pulmonary and extrapulmonary health effects. Their presence and interaction with irritant gases were discussed earlier. Figure 29 shows the data base for the National Ambient Air Quality Standards criteria used by NAPCA [64]; it includes in parentheses the concomitant concentrations of SO_2 found in these studies.

Cohen et al. [130] studied the incidence of asthma attacks associated with pollution from a coal-fueled power plant. Sulfur dioxide,

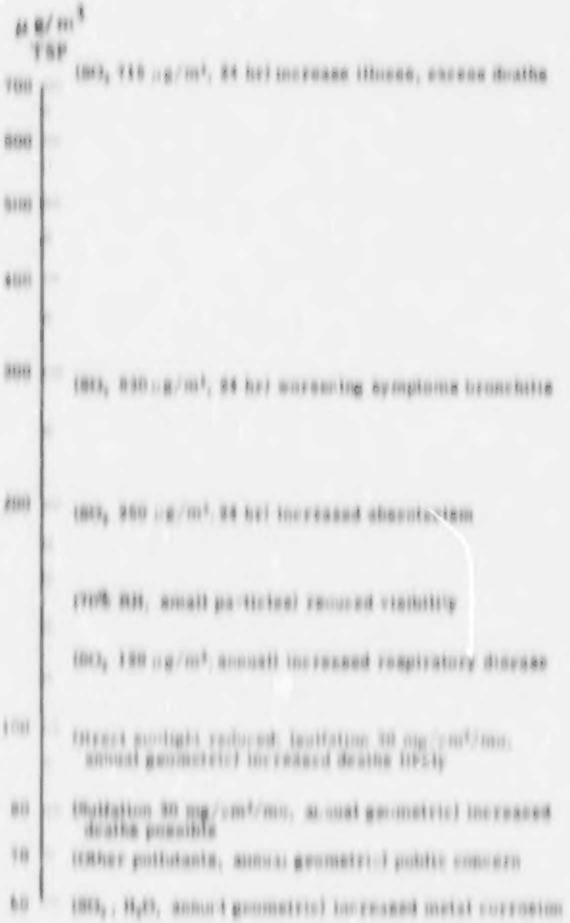

Figure 20. Reference data for particulate air quality criteria [607].

soiling index, total suspended particulates, suspended sulfates and suspended nitrates were each found, by individual analysis, to explain a significant variation in attack rate. However, (low) temperature and any one of these pollutant measures, when taken together (multivariate analysis), eliminated the significant contribution of the others. Temperature alone appeared to be the most significant variable. It was concluded that temperature and pollutant concentrations had a greater relative effect when the temperature was above freezing. This is consistent with the potentiation of pollutant toxicity by higher temperatures reported by a number of investigators.

Sultz et al. [618] found a close association between the continuing exposure to air pollution (defined by TSP level) and the severity of asthma and eczema in children. Jacobs and Langdoc [328] reported an excess of cardiovascular deaths among residents of a highly polluted industrial area (with a variety of particulate pollutants), when compared with cleaner areas.

Lewis and Coughlin [388] studied the acid-insoluble soot contents of male lung samples obtained at autopsy. A mean concentration of total soot for both lungs of 1.7 g was estimated. A statistically significant correlation was found between age and the quantity of soot accumulated, but no association emerged when correction for occupational history and smoking habits were made. Thirteen patients dying with mention of a cerebrovascular accident had accumulated significantly greater quantities of lung soot than the rest of the study population.

Stephenson exposed dogs to wood smoke for various lengths of time [602] and studied the alteration in pulmonary function which occurred.

The pulmonary dysfunction consisted of an early progressive increase in the alveolar-arterial PO_2 gradient and a decrease in compliance. As exposure was prolonged, the respiratory effects were followed by cardiovascular and neural dysfunction. In those animals which survived, the authors noted a decreased resistance to bacterial infection. They did not separate the effects of specific constituents of the smoke (heat, CO, aldelydes, particulates).

As an indication of the hazard from TSP in indoor environments it should be noted that TSP concentrations for one hour have been found in indoor air as high as 462 $\mu g/m^3$ [329] and 539 $\mu g/m^3$ [241]. Elliot and Rowe observed peak concentrations of 620 $\mu g/m^3$ [185]. Penkala and de Oliveira [485], among other investigators, have found that cigarette smoking will increase indoor air TSP concentrations to above the NAAQS ambient standards of 260 $\mu g/m^3$ for a 24-hour average. Since the ambient air standard for particulate is based in part on the health effects of particulate as measured by high-volume samplers, comparisons of indoor particulate concentrations with ambient standards should take into account the size and hence weight, of particulate which enters these samplers. Since tobacco smoke particulate is considerably smaller in size (approximately 1 μm mean aerodynamic cut size) a significantly larger number of these smaller, and hence lighter particles would be required to reach concentrations as high as the ambient air standard. Further discussion of the health effects associated with tobacco smoke appears in Section 8.7.2.

In general, the data on suspended particulates suggest that the quantity, composition, size, and interaction of the particulates with pollutant gases, must be taken into account when evaluating their health hazards.

8.7.2 Tobacco Smoke

Tobacco smoke has been shown to increase the risk of cancer, cardiovascular and other diseases, and to act in a synergistic manner with other chemicals in carcinogenesis. These hazards have been extensively studied from the point of view of their impact upon the smoker. The primary interest in tobacco smoke in this literature review is, however, in its impact as an indoor air pollutant affecting the health of the bystander.

Extensive reviews of tobacco smoke and its adverse affects on human health have been provided by Kilburn [351] and by Schmeltz, Hoffman and Wynder [546]. Kilburn points out that the pyrolysis of tobacco yields over a thousand products, and she considers that the contents of tobacco and smoke condensates are much too complex "to achieve the idea of relating biological effects to single chemical components." Nevertheless, smoke gases and particulates are of interest as composite pollutants, and individual components may constitute a hazard in themselves if they reach sufficient concentration from tobacco smoke alone, or in combination with multiple sources.

Schmeltz [546] found no data suggesting that the passive inhalation of tobacco smoke by non-smokers increases the risk of developing cancer. However, his review cites three studies in which there was an increased incidence of acute respiratory ailments in children and infants, in homes where the parents smoke. Griffin [253] notes that these studies are suspect because of the statistical interference caused by increased respiratory infections among the smokers themselves. However, Griffin cites a further study in which parents' symptoms are controlled and the increased risk of respiratory illness remains. Other effects cited by Schmeltz are eye irritation and chronic respiratory symptoms (in persons particularly sensitive to smoke), and elevated COHb and nicotine levels.

Tobacco smoke has the potential for causing a wide spectrum of adverse health effects, since smoke contains carcinogens and cocarcinogens, ciliotoxins and other agents implicated as contributing to an increased incidence of cardiovascular disease and emphysema. Cigarette smoke has been implicated as a source of cadmium in human tissue. Accidental exposure to cadmium fumes can cause acute lung damage of the severe central-lobular emphysema type. Hayes et al. [279] exposed rats to a polydispersed aerosol of 0.005 in cadmium chloride for two hours. They noted a one-hour peak of malate dehydrogenase activity (which may indicate specific mitochondrial injury) and after two hours, type II cell proliferation and elevation of glucose-6-phosphate dehydrogenase. They concluded that more than one mechanism (effect) may be operating.

Most interest in tobacco smoke has been confined to CO as the major hazard although more recently it is recognized as an indicator of smokers pollution as well as a hazard in itself. Schmeltz cites a number of studies which indicate that those more susceptible to oxygen deprivation, such as cardiacs and anemics, may develop dangerously elevated COHb levels from passive inhalation [546]. The controversy surrounding the hazards of indoor tobacco smoke concerns whether these persons should ever be exposed to such concentrations, produced by others.

An important concern with tobacco smoke is the possible adverse effects following chronic, low level exposure to tobacco's separate components. Nicotine is the most prominent in terms of volume and has been found in indoor air in concentrations as high as 10.3 $\mu g/m^3$ (Section 4.0). Others of particular interest are NO_2, the several existing nitrosamines, and their possible conversion in the air or body to other known carcinogenic nitrosamines.

8.7.3 Trace Metals and Minerals

The respiratory intake of lead has been of concern because of widespread generation from automotive sources. Research relative to the problem of atmospheric lead was reviewed by a committee of the National Academy of Sciences [457]. They concluded that, at present ambient levels, lead inspiration did not represent a clear cut significant problem, but that further research was required on acceptable body burden and the related potential long-term effects.

The TLV established by The American Conference of Governmental Hygienists for lead is 200 $\mu g/m^3$ [14]. The work of Shapiro et al. [562] gives some hint of the importance of lead as a pollutant in the urban society. The authors examined the teeth from seven Egyptian mummies and teeth from modern non-industrialized Indians from the Lacandon Forest in Mexico. These two groups had similar and low concentrations of lead in their teeth. A comparison with teeth from a modern, industrialized, U.S.

population, revealed a 45 fold increase in the later group's dental lead concentration.

Inspired lead is absorbed by the pulmonary bloodstream. The degree of absorption is related in main to the proportion of lead dust particles less than 5 μm in size and to the individual's minute volume. Increased workload therefore results in higher lead absorption.* More than 90 percent of the lead in the bloodstream will be held by the erythrocytes but lead has a preference for bone and accumulates in bony tissue. Thus the lead effects on the hemopoietic system include a decreased hemoglobin content, a decreased number of erythrocytes and an increased number of reticulocytes.

The chief early symptoms of lead poisoning are non-specific and include diminished physical fitness, fatigue, sleep disturbance, headache, aching bones and muscles, and digestive upset including anorexia. As severity of poisoning ensues the disease will manifest itself in increased signs and symptoms particularly involving the gastrointestinal tract and the peripheral and central nervous systems.

Except in patients with anemia, the first clearly defined signs of lead poisoning usually do not occur at a blood lead concentration lower than 80 μg/100g of whole blood. However, certain chemical changes can be demonstrated at levels below 40 μg/100g and possible subtle effects on health and behavior are postulated. Two categories of people may be subject to exceptional risk: workers exposed to unusually high ambient concentrations associated with their employment, and infants and young children exposed to lead in street dust. The latter group can probably ingest and inspire sufficient lead to increase body burdens above a safe level. On the basis of available epidemiological evidence, it was not possible to attribute any increase in blood lead concentration to ambient lead air pollution exposure below a mean concentration of about 2 or 3 μg/m^3 - only small groups of people have been identified as being exposed to higher ambient concentrations than these. A special case of exposure, studied by Bridbord and Shy [85] concerns the burning of candles with lead-core wicks. Concentrations were observed to reach 20 μg/m^3 in an indoor home environment.

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* Occupational Health and Safety, International Labour Office, Geneva, Switzerland, 1972.

Kopple et al. [358] have reported on a series of metabolic studies designed to evaluate the relative contributions of inspired and dietary lead to body burden. Using three techniques to calculate inspired lead, intake when breathing normal urban air was estimated as high as 18 ± 3 μg per day, suggesting that a person can incorporate a substantial quantity of lead from inhalation of the ambient urban atmosphere. The authors point out that despite the relationship shown with body burden usual ambient lead levels have not been established as a health hazard.

Bogen et al. [75], in studying exposure of New York City residents to lead, concluded that inhalation was the principal source of stable lead intake. In a study of occupationally exposed persons, Johnson et al. [338] found that lead and cadmium content of excreta, blood and hair were correlated with airborne levels of these metals, but zinc, manganese and copper were not. Angle and McIntire [33] compared blood lead levels of urban and suburban children of various ages. Urban children had higher levels, the difference decreasing in the older age groups. No significant difference was found between urban and suburban sites in the lead content of air, house dust, milk or water, or in available paint chips. Increased blood lead levels for urban children were correlated with lead in urban dust fall, yard soil and boot trays. Yard dirt and blood lead levels were associated with residential proximity to traffic. Although all blood levels were less than 40 ug, enzyme studies supported evidence for decreased red blood cell survival at the levels found in urban children.

Excessive levels of aluminum from air conditioner deterioration have been noted as a potential indoor hazard. Hamilton and Hardy [266], in reviewing studies on this metal, cite reported cases of interstitial pneumonia, pulmonary fibrosis, severe aluminum pneumoconiosis, and emphysema from industrial exposures. Effects are apparently limited to respiratory damage and severity is dependent on dose and particle size. Many of the reports on the pulmumonary effucts of aluminum are from the aluminum abrasives (Al_2O_3) industry where a progressive, non-nodular interstitial fibrosis (Shaver's Disease) has beun noted among workers.* Since exposure in all cases was not only to aluminum oxide but to silicon dioxide and to iron fumes, the role of aluminum as thw etiologic agent of Shaver's Disease remains unclear. In the U.S., aluminum is considered non-toxic and regulated as a nuisance dust, with exposure limitations of 15 mg/m^3. As inhaled aluminum reaching the lung appears to remain there, the effects of a cumulative burden must be considered.

In reference to hazards from air conditioning it is interesting to note, although biological contaminants have not been treated in this review, the work of Banaszak [52] who reported four cases of a hypersensitive pneumonitis among workers in the same office that was eventually traced to contamination of the air conditioning system with a thermophilic actinomycete. Since that time four additional cases have been encountered, three of which were verified as due to this group of agents in home air conditioners or furnace humidifiers.

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* Occupational Health and Safety, International Labour Office, Geneva, Switzerland, 1972.

Many other toxic trace metals are found in urban air but do not appear to obtain sufficient concentrations to be of concern, unless there is an unusual local source. The use of *platinum* and *palladium* in automotive catalytic converters has raised the question of their importance in ambient air and studies are underway to assess concentrations, body burden and toxicity [337, 305]. Hamilton and Hardy [266] indicate toxic reactions to palladium were only produced in animals after injection and there are no current reports of ill effects in workers. Platinum has resulted in dermatitis and asthma in workers with occupational exposures.

Asbestos and *talc* have been associated with neoplasms in persons exposed to occupational concentrations, and asbestos with nonoccupational exposures [559].

Asbestos is a broad term embracing a number of fibrous mineral silicates that differ in chemical composition. The three types of greatest commercial importance are chrysotile, a hydrated magnesium silicate; crocidolite, a sodium iron silicate; amosite, an iron magnesium silicate. Chrysotile is the most widely used. The TLV of asbestos is 5 fibers longer than 5 μm per milliliter [14].

The hazardous effects of exposure to asbestos of industrial workers have been demonstrated repeatedly since the 1920's. The clinical consequences are generally considered to be of three types:

1. A potentially disabling pneumoconiosis characterized by a "restrictive" pulmonary functional pattern with reduced total lung capacity, lowered vital capacity without evidence of airway obstruction, reduced compliance and impaired transfer factor for carbon monoxide.*

2. Bronchogenic carcinoma [558]. Enterline [191], in a discussion of the methodologic difficulty of precisely relating exposure to asbestos and carcinoma, states that while most agree there is an excess of the disease in exposed persons, the magnitude of the excess related to exposure is not clear. Many believe [565]* that there is a clearly greater risk of cancer of the upper respiratory tract in asbestos workers who also smoke.

3. Mesothelioma, a diffuse carcinoma which invades the pleura and sometimes the peritoneum.

As previously noted in Section 4.0, Nicholson [467] reported measurements of asbestos fiber concentrations of between 100 and 5,000 $\mu g/m^3$ in the air of homes of asbestos workers. Additionally, 500 fibers/ml. were observed in a building which uses a rotary asbestos heat exchanger. Other important potential sources of asbestos dust in the home are the use of insulation and fire-proofing materials in standard construction. Brake lining wear also introduces asbestos fibers into ambient air. Selikoff [558] cites several reports which confirm the deposition of these fibers in the lungs of the general population; he and his colleagues examined relatives living in homes of amosite asbestos workers and found asbestos-related pathology in 38.6 percent of the first 210 persons studied. Selikoff reports that data are now becoming available that will permit relating the degree of asbestos exposure to lung burden.

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* Occupational Health and Safety, International Labour Office, Geneva, Switzerland, 1972.

Occurrences of a nonoccupational risk from asbestos dust have been reported from Britain and France; a few cases of mesothelioma have occurred in persons who were living near a source of asbestos dust or who were exposed at home, from dusty clothes brought back from work [631, 137].

An important finding in the production of tumors by asbestos has been made by Stanton [599]. Upon comparing the effects of various structural forms of asbestos, fiberglass and aluminum oxide in rats, he found that carcinogenicity was related primarily to the fibrous structure rather than to physiochemical properties. Fibers below 2.5 µm in diameter and 10-80 µm in length were particularly carcinogenic.

Consumer talc products have been indicted as potential hazards because of increased cancer risk among talc workers and because many talc minerals contain asbestos fibers. Stanton [600] has reported the development of an experimental mesothelioma with several varieties of fine fibrous glass. Selikoff [558] concludes that while there is no convincing evidence of cancer risk from inorganic dust (other than asbestos), there are still too few studies on the potential risk, particularly at levels to which the general population may be exposed.

8.8 AIR POLLUTION AND LUNG CANCER

The role of atmospheric pollution in primary cancer of the lung is the subject of continuing controversy. One principal class of causal agents of interest is the polynuclear aromatic hydrocarbons (PAH), many of which are known animal carcinogens. Evidence for the relation of PAH to lung cancer is based on their production of cancer in animals, their presence in tobacco smoke, and the strong statistical association of smoking with increased lung cancer in man. In addition to the argument that this apparently logical sequence of observations does not constitute unequivocal proof, the controversy stems from difficulty in separating the individual contribution of more usual atmospheric pollutants from those related to smoking and to occupational exposures.

Research on particulate polycyclic organic matter (POM) was subjected to intensive review by a committee established by the National Academy of Sciences [459]. It was concluded that there is an "urban factor" in the pathogenesis of lung cancer in man and that benzo(a)pyrene (BAP) could be used as an indicator molecule implying the presence of polycyclic organic carcinogens. However, the NAS committee believed that these substances had not been shown to be teratogenic, and the presence of hydrocarbon mutagenesis and carcinogenesis had not been proven to be closely related.

Carnow and Meier [107], in a statistical study relating BAP to lung cancer in the U.S. and 19 other countries, estimated that an increase of 1 μg/1000 m^3 in concentration of BAP was associated with a 5 percent increase in lung cancer mortality. (These data were used as the basis for the Academy's recommendation for a working exposure-response hypothesis.)

Hirayama [297] has reported on a series of epidemiological studies of lung cancer in Japan. In one prospective study the data indicated that the risk of lung cancer increases 10 fold if atmospheric contamination is added to cigarette smoking. Sterling [602] published a critical reassessment of smoking and lung cancer, suggesting that the evidence was weaker than popularly viewed and citing many studies which evaluated the important contribution of occupational and other atmospheric pollutants. Subsequent rebuttals were made by Weis [683], Higgins [290], and Bross [92]. Some of the material related to the discussion in these papers concerned trends in respiratory cancer mortality reported by Higgins [291].

The increased risk of lung cancer associated with cigarette smoking is accepted by most of the scientific community, although the particular constituents responsible have not been established. Polycyclic aromatic hydrocarbons (including BAP) in the smoke are considered a primary candidate. These compounds are highly carcinogenic in animals and recognized as a cause of occupational skin and cervical cancers [459]. Implication of PAH in inhalation carcinogenesis has been reported for gas workers and men working at coke ovens, and workers heavily exposed to printing ink [459]. Most evidence for a role of other air pollutants in lung and upper-respiratory cancer has also involved occupational exposures, e.g., radon daughters, asbestos, haloethers, nickel, chromium. Although the high exposure levels concerned would seem to make many of these factors inapplicable to the nonindustrial indoor environment, evidence is accumulating on nonworkplace risk of respiratory cancer.

Blat and Fraumeni [73] have reviewed data on arsenical air pollution and lung cancer. They cite studies indicating an excessive risk in smelter and pesticide workers. These data led to an analysis of lung cancer mortality patterns in communities with arsenic-emitting smelters which suggested an increased incidence of lung cancer in residents of these areas. Selikoff cites work of his own associates, and others, which indicates significant asbestos levels and increased mesotheliomas in families of asbestos workers and residents of areas near asbestos industries [550].

The report of an association of respiratory cancer and sulfur compounds by Winkelstein et al. [701] was discussed earlier. In this regard, SO_2 has been demonstrated as a co-factor in carcinogenesis with BAP [458] and with arsenic (cited by Blat and Fraumeni [73]). This work provides further evidence of the hazard posed by sulfur oxide-particulate combinations.

8.9 SUSCEPTIBILITY OF POPULATION SUBGROUPS TO INDOOR AIR POLLUTION

Consideration of those population groups particularly susceptible to pollutants requires that certain facts be borne in mind:

- There is a wide variation in the susceptibility of different persons to air pollution
- Preexisting or underlying disease conditions augment the stresses added by air pollution
- Under some conditions, some types of air pollution cause structural damage and persistent disease in well persons.

The primary population groups most effected by air pollutants are those which have underlying disease of the organ systems involved in the absorption, clearance and deposition of the polluting agent.

By far the most seriously affected population is that with pulmonary disease - such as chronic obstructive pulmonary disease, bronchitis or emphysema - since the most fruquent route of absorption of air pollutants is via the respiratory tract. This is evident from studies of the effects of severe episodes of air pollution, such as that which occurred in London in 1952 [429]. There was a dramatic increase in the mortality of those with chronic lung disease at that time. Lawther [376] and Glasser [240] have presented evidence that during less severe episodes of air pollution (in London and New York) in many patients severe chronic respiratory disease is aggravated. Individuals with pulmonary emphysema have some degree of decreased dynamic compliance, increased airflow resistence, ventilation/perfusion abnormalities, etc. Many of these patients often have a reduced arterial oxygen saturation, usually with a concomitant increase in PCO_2 [57]. Thus it is evident why their fragile physiologic situation is adversely effected by air pollutants of various types such as SO_2, NO_x, and CO.

Asthmatics are patients with a disease characterized by intermittent bronchoconstriction and increased viscosity of bronchial mucus. There is evidence that many common pollutants, including inert dust [173], tobacco smoke and SO_2 [443] cause bronchoconstriction and thus tend to aggravate the preexisting condition.

Patients with low cardiac reserve due to chronic cardiovascular disease, or with elevated COHb levels, can be jeopardized by high ambient CO levels. Other groups, such as those with anemia or cirrhosis of the liver, will suffer deleterious effects from agents which react with the hemopoietic (CO) or hepatic (carbon tetrachloride) systems.

The older-aged population appears to be more susceptible to the adverse effects of air pollution. The extent to which this phenomenon is related to the increased incidence of cardio-pulmonary disease in this age group, or to other factors related to the aging process and increased infirmity, is not totally clear.

Douglas and Waller [167] followed 5,000 children from birth to age 16 and studied the incidence of morbidity from respiratory disease. They found a clear-cut association between an increased rate of lower respiratory tract infection and the degree of air pollution in their environment. Other studies for example, the work of Lunn et al. in Britain [399], have confirmed this relationship. Children also seem more affected by other pollutants, such as lead. To some degree this observation may be related to absorption routes such as paint chip ingestion, less likely to occur in adults. Although the factors in lead intake and balance are not well established, children or workers who may already have a high blood level could possibly achieve clinically important burdens from respiration of ambient concentrations.

Further work appears warranted on the effects of air pollution on those persons with preexisting depression, hypersensitivity states of various types, and collagen disease [98].

8.10 INTERACTIVE POLLUTANT EFFECTS

The interactive effects of combinations of pollutants have been noted by many investigators and have been discussed in this literature review in the reporting of research into the health effects of individual pollutants. In summary it may be said that the synergistic action of particulates and SO_2 seems to be well established. Some evidence is available implying a similar action between particulates, NO_2, and oxidants. Hackney et al. [259] found no significant differences in human volunteers exposed to O_3 and combinations of O_3, NO_2, and CO, although these experiments could not be considered adequate. The studies available suggest an additive or synergistic effect on lung cancer of exposures to POM from smoking, occupational pollutants, and ambient pollutants.

Several studies have investigated the contributions (individual and in combination with pollutants) of temperature and humidity. The CHESS studies and others have been cited which imply that the ambient pollutants contribute more to aggravation of respiratory disease at higher temperatures. PAN appears to be more potent at higher temperatures. In a review by Green [249] of studies on the effects of indoor humidity, it was concluded that increasing the relative humidity of occupied spaces from 20 to 50 percent reduces the relative incidence of respiratory conditions among school children.

Burch [98] and Randolph [509] have been concerned with the exposure to myriad chemical substances in the home. From his clinical observations, Burch feels it is evident that home pollutants play a role in autoimmune, collagen, and cardiovascular diseases. Randolph reviewed the ecological basis for mental illness and describes a comprehensive environmental control approach to managing mental problems. He presents a lengthy case listing in which sensitivity to a wide variety of agents in the patient's home was involved. Randolph describes the often subtle progression to chronic symptoms. The extent of substances to which hypersensitivity may occur is illustrated by cases reported by Randolph:

- Gas appliances (many cases)
- Hair spray
- Perfumed toilet paper
- Plastic furniture and curtains
- Chlordane for termite control
- Noise from electric appliance motors
- Petroleum distillate for house dust control
- Many pesticides, insecticides
- Refrigerants (probably a Freon)
- Foam rubber and hydrocarbon vapors
- Textiles
- Creosote, adhesives, bleaches, ammonia, mothballs, and such miscellaneous household products.

8.11 EVALUATION OF INDOOR AIR POLLUTANT HEALTH HAZARDS AND RESEARCH PRIORITIES

One major objective of this study was to develop an overall relative evaluation of specific indoor pollutant hazards, based on the current state of knowledge, that would permit identification of research priorities. The intent was to document a series of pollutant problems that might be assigned degrees of importance in terms of potential impact on human health considering the anticipated severity of effects, scope of population concerned, feasibility of further definition, and similar factors. In the abstract some definitive and comprehensive pursuit of this objective seems realizable but, as will be discussed, only a partial resolution has been achieved here.

A methodology for a realistic ordering of the relative hazards from the various identified air pollutants which may occur in indoor, non-workplace environments will require at least the input information shown in Table 45.

A ranking cannot be made without assigning numbers, however crudely defined, to the elements being ranked. There are obviously gigantic problems in obtaining numerical answers to the questions implied in Table 45. Assuming for the moment that such numbers could be obtained - which may not be a valid assumption - a model of an indoor air pollutant hazard rating procedure might contain the elements and interrelationships for examination of each identified indoor air pollutant which are shown in Figure 30.

TABLE 45. ELEMENTS OF A POLLUTANT HAZARD RANKING METHODOLOGY

1. Identification of the full set of all the important air pollution-related adverse health responses, and of the air pollutants associated with them.

2. Development of sets of exposure-response functions for each air pollutant (and for combinations of pollutants) with the responses delineated as a graded series, of increasing severity for increasing exposures, for various classes of the potential population at risk, such as

   - normal healthy individuals
   - young children
   - elderly people
   - individuals with special respiratory, cardiovascular, or other health problems. (This class will be divided into an appropriate number of subclasses.)

3. Development of criteria and a schedule ranking severity of response in terms of undesirability from the point of view of society as a whole. Elements of this ranking might include:

   - level of disability (mild discomfort to death, in graded intervals)
   - duration of disability
   - time from exposure to onset of disability
   - value to society of affected individual (unless it is assumed, for example, that chronic disability of a child, an economically active adult and a bed-ridden elderly person are all of equal disbenefit to society);

4. Estimates of the total numbers of people in the United States in each class and subclass defined in Item 2.

5. Definition of graded sets of quantified air pollutant exposures, corresponding to the various graded sets of response severities developed in Item 3. These sets of exposures must be expressed not only in terms of total quantity of pollutant but also in terms of intensity and duration of time intervals between exposure and response.

6. Mobility estimates for each class of the population identified in Items 2 and 4, defining the total amount of time spent by the population of each class in nonworkplace indoor environments.

7. Determination for (each air pollutant and combination of all pollutants identified in Item 2) of a graded series of indoor pollutant concentration levels, for short-term and long-term durations, which - when multiplied by time spent in indoor environments by the average member of each population class (see Item 6) - would result in the various graded sets of air pollutant exposures corresponding to different severities of health response as defined in Item 5. (The indoor air pollutant concentrations so defined would in effect be graded concentration hazard levels for indoor air pollutants and as such could become the basis for indoor air quality regulations.)

8. Estimates of the frequency with which indoor concentrations of each air pollutant, and combinations of pollutants, equal or exceed the various graded pollutant concentration levels (determined in Item 7) in the totality of nonworkplace indoor environments in the United States.

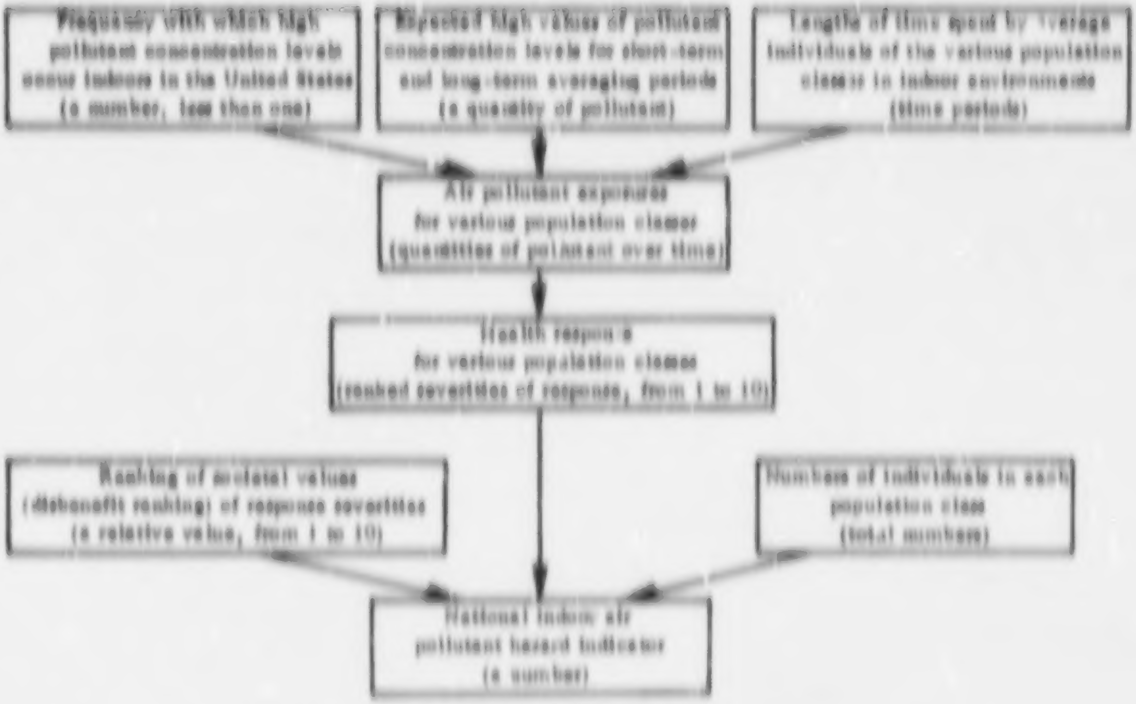
Frequency with which high pollutant concentration levels occur indoors in the United States (a number, less than one)
Expected high values of pollutant concentration levels for short-term and long-term averaging periods (a quantity of pollutant)
Length of time spent by average individuals of the various population classes in indoor environments (time periods)
Air pollutant exposures for various population classes (quantities of pollutant over time)
Health response for various population classes (ranked severities of response, from 1 to 10)
Ranking of societal values (disbenefit ranking) of response severities (a relative value, from 1 to 10)
Numbers of individuals in each population class (total numbers)
National indoor air pollutant hazard indicator (a number)

Figure 40. Elements of a pollutant hazard rating model.

The functions relating sequential elements of this model would be complicated. In some boxes of the model there would be a need to develop weighting factors; for example, if a pollutant occurs frequently at high concentrations in one critical type of inhabited indoor environment but almost not at all in other environments, it might be desirable to give it a higher frequency credit than the absolute numbers of its national frequency of occurrence would suggest.

A ranking of relative pollutant hazards in indoor environments would be obtained by (1) performing the calculations implied in this model for each pollutant and combination of pollutants specified earlier in Item 2 of Table 45, and (2) comparing the resulting hazard indicator numbers.

Having described a conceptual approach to the ranking of indoor air pollutant hazards it is now necessary to say that in our opinion with the current state-of-the-art no formal, logical ranking is possible. The major reasons for this are:

- The amounts and quality of data available to answer the questions implied by Table 45 are highly variable. The pollutant concentration characteristics of typical indoor environments are only just beginning to be explored. For some pollutants, such as carbon monoxide, something is known about frequencies of occurrence and indoor concentrations and much is known about exposure-response functions for various population groups, but for many other pollutants - such as respirable fractions of particulates, and most of the organics - far less is known.
- It is not yet possible to forecast the long-term effects (particularly in low concentrations) of many agents, especially of those chemicals (such as those in pesticides and aerosols) that have more recently come into general use.
- The ranking of health response severities in terms of social values will be extremely difficult. Criteria such as level of disability will be judgmental, even more so will be the weight given to time before onset of disability. General acceptance of criteria for ranking severity of response would be difficult to obtain.

The problem is also complicated by the consideration that research priorities cannot be based solely upon present pollutant exposures, but must anticipate trends. For example, shifts from low to relatively high sulfur fuels in energy production, required to meet a larger portion of national energy needs with domestic resources, may suggest a renewed interest in SO_2 and sulfate pollution research which would not be engendered solely by consideration of present needs for health effects research in sulfur oxides vis-a-vis other potential indoor pollutants.

We have now described (1) a conceptual approach to hazard ranking of pollutants and (2) reasons why we are not prepared to pursue a quantitative implementation of this approach. However, there remains a need for the scientific community to make judgments about priorities of research in the field of indoor air pollution. An effort is made in the following paragraphs to make some provisional rankings, unsupported by numerical analysis, which draw upon the principles outlined above and upon the large body of research reviewed in this study.

In the most general sense, evaluation of indoor pollutant hazards must encompass study of all ambient pollutants plus many of those that occur in industrial processes. The scope of this perspective, when taken with the sparse data on exposure levels and long-term effects, has led to the conclusion that a chemical-by-chemical approach is beyond the capabilities of this project. However, by focusing on unique aspects of indoor pollution brought out in the review, and by applying some of the principles of the formal approach without hard numbers, it is possible to make broad, general recommendations on research priorities. These recommendations consider the following factors for the several major classes of indoor pollutants:

- The size of the population exposed
- The anticipated health impact at estimated common indoor exposure levels
- The unknown factors important for further study
- The apparent advantages or difficulties for further research suggested by the review.

On this basis, and considering only those pollutants which have potential for unique indoor concentrations, we would rank pollutant groups for further investigation in the following order of decreasing priority.

1. Carbon Monoxide, Nitrogen Oxides, and Sulfur Oxides

These ambient gases (and the transformation products of NO_2 and SO_2) present a potential hazard to large populations, particularly in urban areas. Substantial amounts of the gases may be generated from indoor sources, primarily from the use of fossil fuels in cooking and heating appliances. Carbon monoxide is also a major component of tobacco smoke. These gases affect both the respiratory and cardiovascular systems and therefore have a deleterious effect on two of the largest susceptible population subgroups, those with clinical disease of these types. While a great deal is known, significant questions remain, i.e., their synergism with each other and with other agents and the relation of temperature and humidity to their action.

2. Tobacco Smoke and Its Products (In Addition to CO), Such as Polynuclear Aromatic Hydrocarbons (PAH), Cadmium, Nicotine, and Nitrosamines

Since a large proportion of the adult population continues to smoke, particularly in the indoor milieu, many nonsmokers are also exposed. In addition to its adverse effects on patients with cardio-respiratory disease, cigarette smoke has been indicted as a causative agent in bronchogenic carcinoma, and apparently is contraindicated in those with hypertension.

The role of each specific byproduct of tobacco smoke is not well understood, nor is its apparent synergism with other pollutants. Until these questions and others are answered, the process of correcting its toxicity, or of successful public education, will be difficult.

3. Pesticides: Chlorinated Hydrocarbons and Organophosphates

The accelerated use of these agents over the past three decades, has greatly increased the potential exposure in the indoor environment. Many of these agents are widely dispersed in indoor spaces and tend to persist for long periods of time. Further study, particularly of their long-term human consequences, is warranted.

4. Trace Metals and Minerals, Particularly Lead, Cadmium, Arsenic and Aluminum

The population exposed to these agents is large, particularly to those arising from automotive exhausts (lead) and cigarette smoke (cadmium). While other agents in this group (asbestos) cause severe clinical disease in the human, they probably do not affect large numbers of people. Much is yet to be learned regarding their long-term effects in low concentrations.

During the initial stages of the literature review upon which these recommendations are based it appeared that the rapidly increasing use of fluorcarbon propellants in indoor environments, coupled with the lack of information about the possible health effects of repeated high short-term exposures, would justify further study of the health hazard of fluorcarbons in the indoor environment. However, action now being taken by the U.S. Food and Drug Administration (and by officials in other countries) to phase out the use of fluorcarbon propellants in consumer products - largely because of potential damage to the ozone layer - has probably mooted their problem.

It is apparent from our literature review that establishment of the degree to which in fact, current or future indoor pollutant levels pose a serious hazard to human health must await documentation of (1) the actual exposure histories of various categories of persons and (2) demonstration that such individual and combination exposures overcome physiological defense mechanisms to produce adverse effects. Many of the chemicals reviewed have been given low priority because of the difficulty in identifying adverse health effects from long-term, low-level exposures, and because of the lack of any convincing evidence that their presence as air pollutants at the probably concentrations experienced would pose a health hazard. This would include a wide variety of cleaning and hobby materials that may be hazardous if normal precautions are not taken or if ingested or subject to lengthy skin contact.

The selected ambient gases were given highest priority because of documented indoor concentrations and documented adverse human responses at those levels. It seems important, from an epidemiological view, to now determine actual exposure and absorbed dose considering pollutant and occupant behavior. The situation appears to offer several unique advantages for study of health effects in that contrasting exposure conditions within the same study community might be defined, based on combinations of indoor and outdoor sources. This would take into account not only the factor that gas appliances may add appreciable quantities of pollutant to the indoor spaces (and thus total exposure) but the converse hypothesis that spaces with electric appliances and reduced outdoor infiltration (say, because of air conditioning) may provide significant shelter from the more reactive gases.

The remaining priorities were not as clear-cut. Tobacco smoke seemed of importance because of the variety of toxic agents, the amount of pollution generated, the established long-term effects in smokers, and the seemingly high potential for adverse effects in bystanders. The other three groups are considered to be about of the same order of hazard. With these latter agents it is important to determine the actual extent and nature of exposure in indoor spaces before pursuing further health studies.

Section 9.0

MODELING OF INDOOR AIR POLLUTION

An important purpose of indoor air pollution research is the improvement of ability to predict pollution impact and to propose actions which reduce adverse impacts before such impacts occur. Research described in earlier sections of this report has accumulated observations about indoor air pollution, building energy and occupancy characteristics, and the health effects of air pollution. Observation and measurement are essential elements of an understanding of the indoor air pollution problem. By themselves they are inadequate as guides for prediction and control of indoor air pollution. For those purposes the observed facts must be synthesized into predictive methodologies.

9.1 OBJECTIVES

Methods are needed for problem definition and for estimating the probable environmental outcomes (indoor pollutant concentrations, energy costs, pollutant exposures, and health effects) which may accompany measurable conditions (outdoor pollution, indoor pollutant sources, building characteristics, and human activity) affecting the indoor environment. A method through which a quantified, generalized definition of a complex problem can become the basis for calculating presently unknown outcomes as the simultaneous or subsequent concomitants of known or assumed initial conditions is by definition a model. An important thrust of indoor air pollution research is directed toward modeling.

A planner who proposes to intervene in a specific indoor environment to improve energy conservation, air quality or health will be concerned with questions such as:

- What energy conservation measures and results are possible?
- What levels of temperature and humidity may occur?
- What air pollutants may occur indoors, at what concentrations, times and places?
- What will be the durations and intensities of human exposure to these conditions?
- What are the probable adverse health effects of such exposures?
- What interventions are possible for the mitigation of adverse impacts?
- Which adverse health effects are the most undesirable; i.e., what are the priorities for selecting alternative outcomes and interventions?
- What specific data must the planner have about present and future conditions in order to make rational decisions for improvement of thu indoor air environment?
- How sensitive are the outcomes of the predictive methodology to inaccuracies in the measurement or assumption of initial conditions?

Questions of this kind can be addressed through modeling.

9.2 LIMITS OF CURRENT RESEARCH

There is a literature of scientific research in the modeling of indoor energy use and indoor air pollution. At least 16 building energy models, 3 building ventilation models and 5 indoor air pollution models have been developed. Reports of these research efforts are described in detail in Appendix A of this report. The reader who wishes a detailed mathematical treatment, particularly of the ventilation and air pollution models, is referred to the Appendix. Table 46 provides a summary description of the five existing classes of indoor air pollution models, with their inputs, outputs, and assumptions. Rather than report upon this specialized research in depth in the main body of the report, the presentation which follows describes the general background and principles of indoor air pollution modeling.

Models have been developed which describe indoor energy use and ventilation in terms of building characteristics, meteorology and occupancy. Modeling research in indoor air pollution has defined pollution concentrations as functions of ventilation (and other enclosure characteristics), initial pollution levels, and pollution decay. In a thumbnail sketch, this is the state-of-the-art of indoor air pollution modeling.

Models do not yet exist for calculating human exposure to indoor air pollution in typical, real environments, although efforts to develop such models are currently being planned in the EPA Health Effects Research Laboratories.

Models to describe changes in human health status as functions of indoor air pollution (an even further step) would need to consider not only indoor pollutant exposures but also the exposure history of each individual to outdoor and workplace air pollution as well as many other aspects of the individual's health and environmental history. The complexities of this problem are beyond the capability of integrated modeling efforts at this time. A workable outdoor-indoor air pollution human exposure model,

TABLE 9A. INDOOR AIR POLLUTION MODELS – INPUTS – OUTPUTS – ASSUMPTIONS

Model (Generic Name)	Input Requirements	Model Outputs	Assumptions	References
Effective Residence Time	Volume of structure rate of entry (egress) initial concentration of pollutant	Indoor pollutant concentration time history	Instantaneous pollutant generation, ambient air pollutant free, no sinks, no forced ventilation system (i.e., one structure "breathing" rate including both ventilation and infiltration)	C.H. Milly 1955 [[illegible]] Commons 1971 [[illegible]] Dotson et al. 1972 [[illegible]] and others
Dosage Model	Interior Volume, filter efficiency, air intake/exhaust rate, removal rate, indoor source strength, ambient concentration	Indoor pollutant concentrations in a specified time	Constant values or ambient pollutant concentrations over a predetermined time interval is assumed in the definition of dosage	R.L. Calder 1961 [[illegible]] Milly and Threw, 1967 [[illegible]]
The "Well-Mixed" Jar Model	Chamber volume, initial pollutant concentration, source strength, ambient concentration, number of air changes, mixing factor	Concentration of pollutant in the chamber at any time	Perfect mixing is assumed in the chamber; nine theoretical cases are analyzed, each one involves a different assumption	A. Turk 1963 [[illegible]]
The "Black Box" Model	Volume, ambient concentration, volumetric rate of intake/exhaust systems, indoor source strengths, rate of air recirculation	Rate of change of total concentration of the pollutant in the enclosed volume	Model applicable only to structures with forced ventilation systems and positive indoor pressure, no infiltration/exfiltration terms, no sink terms	Shair et al. 197[illegible] [[illegible]] Shair and Heitz, 1974 [[illegible]]
The Linear-Dynamic Model	Indoor volume, filter efficiency, indoor surface area, indoor source strengths, outdoor concentrations, infiltration/exfiltration rates, intake/exhaust rate, recirculation rate	Indoor pollutant concentration as a function of time	A first order decomposition mechanism for ozone is the only sink mechanism considered	Shair and Heitz 1974 [[illegible]]

used in conjunction with epidemiological studies of human populations, might represent the greatest extent to which simulation modeling can be applied to the indoor air pollution health effects problem in the near future.

This report is intended as an assessment of the state-of-the-art of current research. The discussion which follows is therefore limited to what is presently possible; the predictive modeling of indoor air pollution concentrations.

9.3 ELEMENTS OF INDOOR AIR POLLUTION MODELING

Indoor air pollution models simulate the changes in air pollution concentrations over time in an enclosed space as a function of three basic variables:

- Ambient (outdoor) air pollutant concentrations
- Indoor air pollutant sources and sinks
- Indoor-outdoor air exchange rates.

The basic variables are in part functions of other variables: meteorology, ambient air pollutant sources, enclosure design (location, size, materials, openings, construction techniques); heating, ventilation, air conditioning (HVAC) characteristics; special energy conservation measures; indoor temperature and humidity; and enclosure occupancy characteristics. These secondary variables are to some extent interdependent. A diagram in Figure 31 illustrates some of these relationships.

Figure 31 suggests the complexity of the conditions an indoor pollution model must simulate. The ultimate question the model answers is: What indoor pollutant concentrations will occur? In the process of answering that question the model must examine such questions, among others, as:

1. To what extent are elevated indoor pollutant concentrations due to ambient pollutants and to what extent to indoor-generated pollutants?
2. To what extent are indoor pollution levels reduced by pollution reducing devices?
3. To what extent are indoor pollution levels affected by energy conservation measures?

The operation of an indoor air pollution model may also provide information (through linkage of occupancy and indoor pollutant concentration data) which defines indoor pollution exposures for occupants of indoor spaces, although a practicable integrated model structured to do this has not been described in the scientific literature.

Figure 11. Major functional relations in indoor air pollution modelling.

The primary output of an indoor air pollution model, pollutant concentrations, can also be obtained by direct field measurements in the environment of interest. The approach is practicable only in a research context. Field measurements are expensive, and they must be conducted over extended periods of time to assure results which reflect a full range of possible input conditions. If the use of the indoor pollution concentration data is to generate personal pollutant exposure information for epidemiological studies of large populations (a use contemplated in several future studies now being considered by the Environmental Protection Agency) it becomes impractical, for reasons of cost and available measurement technology, to plan for direct measurement of pollutant concentrations and exposures for the large numbers of enclosures and people involved. Modeling becomes, in such a case, an essential instrument because only it can provide the necessary answers in a cost-effective approach.

9.4 THE MODELING PROCESS

Indoor air pollution models, as with other models, are likely to be developed in a cyclical approach. Development begins with the definition of candidate input and output parameters, and of such parametric relationships as are known or may be postulated. This is usually followed by the performance of field monitoring studies of inputs and outputs to provide data for the development of a numerical model. These field data help to further define the structure and relationships of the model, which must then be tested against more field data. The goal is eventually to formulate a model which can simulate a large variety of conditions. A general indoor pollution model of such broad power has not yet been formulated. As described in Appendix A, a number of models of limited capacity and varying complexity have been constructed. The fundamental principles involved in these models, their assumptions, the approximations involved, and their constraints are outlined in what follows. Appendix A contains the mathematical expressions involved in each model and provides details which will probably be of interest only to modelers. Readers who do not expect to work with details of the modeling process should find sufficient the material included in this section; for them Appendix A is not obligatory reading.

Air pollution in an enclosure may be of outdoor or indoor origin. If of outdoor origin it enters through infiltration and ventilation. If of indoor origin it is generated from pollutant sources within the enclosure. Regardless of source, air pollutants diffuse in the enclosure. They are removed over varying periods of time by exfiltration and ventilation to the outdoors and through indoor decay. The making of these simple statements marks the beginning of a conceptual model. These concepts are further discussed below.

Air infiltration is defined as the change of air within a structure without the interference of the inhabitants. Thus the ambient air entering an enclosure through cracks in its walls is infiltrated air which, whether clean or contaminated, influences the indoor pollution levels. Ambient pollutants may also be introduced indoors through the ventilation process, which may be defined as air change induced by the occupants of an enclosure; this can be natural ventilation through closing and opening of doors and windows, or can be forced ventilation through the operation of attic fans, air conditioning or heating systems. Air exfiltration is the opposite of air infiltration, in which indoor air leaves an enclosure through structural cracks. Exhaust ventilation moves air from indoors to outdoors through the vents of a forced system as well as through door and window openings. Indoor generation sources such as fireplaces, stoves, smoking, cleaning devices and others introduce pollutants into the indoor environment. Finally, pollutants may be removed from the indoor air environment through indoor decay processes such as chemical transformation, settling, and absorption and adsorption by walls and furnishings (collectively termed pollutant sinks), and by filtering procedures in the make-up air or in the recirculated air.

Three elements are common in all existing indoor pollution models; (1) the mass balance principle is the basis for the model; (2) perfect mixing of pollutants is assumed within the enclosure; that is, no indoor pollutant concentration gradient is assumed in each model; and (3) prior knowledge of all air exchange coefficients is required as an input for modeling operations.

To characterize time-dependent aspects of pollutant behavior it is useful to deal with rates of change of air pollution within enclosures, rather than simply with absolute amounts of pollution. Mass balance principles require that the rate of change of the quantity of an air pollutant within an enclosure must equal the sum of the rates of all processes of pollutant introduction and pollutant removal which operate upon the enclosure. This statement can be expanded into a differential equation - the basic equation of indoor air pollution modeling - which is expressed in words as follows:

The rate of change of total indoor pollutant quantity

equals

The rate of entrance of pollutant in ambient air through ventilation (with or without air cleaning)

plus

The rate of entrance of pollutant in ambient air through infiltration (without air cleaning)

plus

The rate of indoor generation of pollutant

minus

The rate at which pollutant exits through exhaust ventilation of indoor air

minus

The rate at which pollutant exits through exfiltration of indoor air

minus

The rate at which pollutant is removed by air cleaning devices in recirculated air

minus

The rate at which pollutant is removed from air within the enclosure by indoor sinks

Each of the verbal elements of this statement can now become a mathematical element in an equation. The mathematical expressions of this differential equation are not very complex (see, for examples, Equations 55 and 64 in Appendix A), but they involve a series of constants which must be known before solutions of the equation can be undertaken.

A schematic representation of the way in which the terms of this equation act upon a generalized building (or other enclosure) appears in Figure 32.

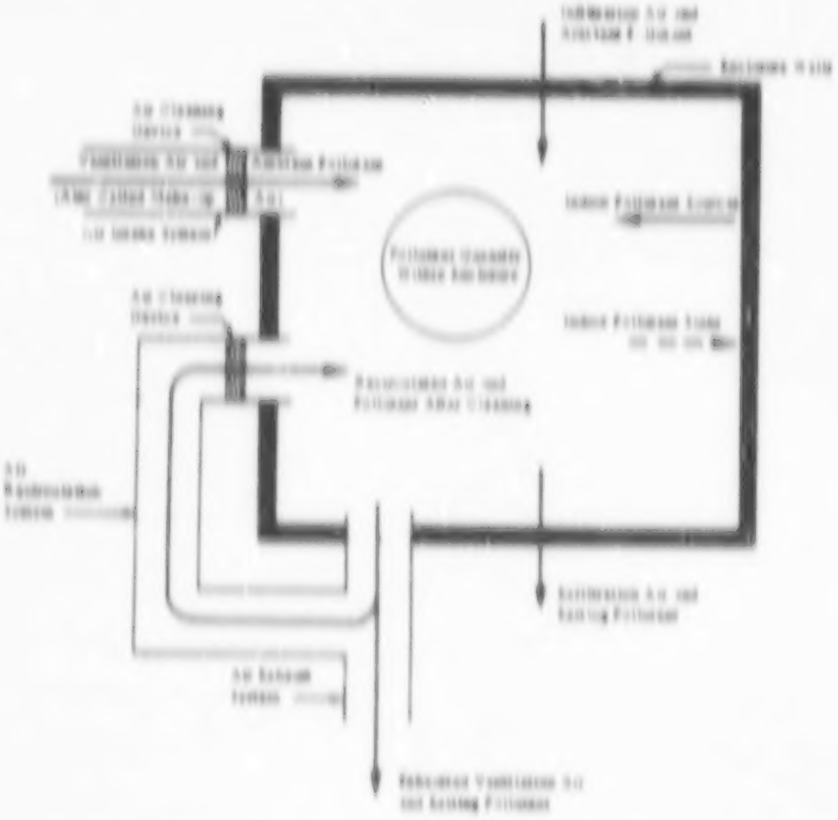

Figure 32. Schematic representation of indoor pollution model equation.

9.5 MODEL PARAMETERS

Determination of values of the parameters involved in the modeling equation (i.e., providing numerical bases for the use of the equation in actual calculation of pollutant concentrations) presents varying degrees of difficulty. There are two principal categories of such parameters, those concerned with structural characteristics of the enclosure and those concerned with pollutant characteristics.

9.5.1 Structural Characteristics

Problems associated with estimating structure coefficients and their constraints upon pollutant behavior (they influence air exchange rates and thus influence pollutant behavior) have often been bypassed in research contexts by limiting modeling application to a single, well-studied structure, or by investigating a very specific problem or a single well-understood pollutant. But the problems of determining equation constants are very significant for the development of general models.

The forced ventilation rate can be calculated from the operational characteristics of the heating, ventilating and air conditioning systems. Natural ventilation rates can be calculated in terms of enclosure size and openings, wind speeds and temperature differentials, as can infiltration and exfiltration rates (although with less assurance). The ways in which human behavior influences ventilation rates (through opening and closing of windows and doors, and adjustment of HVAC systems) have not been quantified for use in existing indoor air pollution models. Filter (air cleaner) efficiencies enter into some, but not all, of the existing models.

Filter factors may characterize pollutant removal make-up air and in recirculated air. Extensive studies on efficiency of filters have been undertaken in the past and there is available literature which indicates how the efficiency varies with time for a large number of filters and pollutants. This has been described in Section 7.0 of this report.

Determination of the infiltration rate, which is conventionally assumed in indoor pollution modeling to be equal to exfiltration rate, can be made experimentally in an enclosure through measurements of the rate of reduction of the concentration of an inert gas released in the enclosure. This is a simple process if infiltration rates are required for only a small number of enclosures. But each house or other dwelling will have its own infiltration rates, and direct measurement of all these becomes impractical if large numbers or relatively diverse buildings are to be modeled. In this case an information matrix relating structural variables to probable infiltration rates must be developed to provide the infiltration rate constants; this has not yet been done in research reported in the literature.

9.5.2 Pollutant Characteristics

The rates at which pollutants are generated within enclosures, and at which they decay, are not well documented. Previous research has described indoor source strengths for combustion-related pollutants such as carbon monoxide and nitrogen oxides; and emissions of pollutants from cigarette smoking and some aerosol spray products have been measured (see

Section 3.0 of this report for examples of available indoor source strength research). Hard data are not available on indoor source strengths of many indoor pollutants.

The least understood term in the indoor pollution model equation is the indoor sink strength. It has been suggested by Dr. Fredrick H. Shair (in a personal communication to the authors in 1976) that for pollutants of low reactivity the sink strength is of secondary importance and that it may be approximated to zero because other processes, particularly air exchange rates, are dominant. Studies of decay rates for sulfur oxides, carbon monoxides, particulates, nitrogen oxides, oxidants, hydrocarbons, and trace metals have been reported in the literature (see Section 4.0 of this report) but the selection of rate constants for specific modeling contexts based upon this research still presents practical difficulties.

Despite the difficulties suggested above, numerical simulation modeling of indoor air pollution promises to be a valuable, cost-effective tool for investigating the causes and impacts of indoor air pollution and - by extension - the health hazards of indoor air pollution.

9.6 CONCLUSIONS

At the minimum, an indoor air pollution model must provide a framework within which it is possible to estimate pollutant concentrations indoors in terms of specifications of corresponding pollutant characteristics immediately outside an enclosed space, and the structural and energy data of the building. It is highly preferable that such a model have broader capabilities, particularly the ability to describe indoor sources and behavior of pollutants. The reviewed indoor air pollution models presently achieve the minimum requirement for a given structure; further research is needed to generalize the application of the models and to extend their capabilities.

The following conclusions can be drawn from the study of existing indoor air pollution modeling research:

- The fundamental principle involved is straightforward (a mass balance equation), and theoretically sound. It has been used by all researchers who have developed indoor-outdoor ventilation and air pollution models.
- All practical applications of the existing models require prior knowledge of a rather large number of coefficients and constants included in the model expressions. Extensive field work is necessary to obtain these necessary factors.
- There are many knowledge gaps. Internal pollution generation and indoor source strengths must be studied more extensively. Indoor sinks (decay rates) need more attention. Indoor pollution levels are affected by energy conservation measurements, by inhabitants; activity factors, by home structural characteristics and others; these relations are inadequately known at present.

The most difficult research problem identified in this appraisal of the literature of indoor air pollution modeling is in the determination of the constants of the basic functional relationships involved in defining structural effects in simulating indoor-outdoor air pollution levels. The reviewed models have generally bypassed this difficulty by considering only one investigated structure, and by experimentally determining the required coefficients for that unique structure. An objective of any new modeling effort should be to formulate a model that may be applied to any given building under varying conditions. The following parameters should be studied and should be connected in model form by functional or associative numerical relationships:

- Outdoor pollution levels
- Indoor generation of pollutants
- Building permeability (ventilation, infiltration rates)
- Meteorological conditions
- Ventilation system capacity
- Building identification parameters, including zones
- Energy conservation factors
- Indoor pollutant behavior
- Human activity factors
- Indoor air pollution control devices.

A model capable of interrelating these factors, using data readily obtainable by state-of-the-art monitoring and field survey technology, and fitted with coefficients of general applicability, would represent a very substantial and important advance over existing modeling capabilities.

Appendix A

MODELING OF INDOOR AIR POLLUTION

A.1 BACKGROUND FOR INDOOR AIR POLLUTION MODELING EFFORTS

Hazards to human health can result from the occurrence, behavior and impact of air pollution, including, of course, that occurring indoors. The hazard levels vary in a complex, not well-understood manner, in which the kinds of pollutants, their concentrations and dosages, and their synergisms with other pollutants and other conditions affecting humans play a part.

Two important objectives in studying indoor air pollution are (1) to obtain a better understanding of the potential health hazards involved and the circumstances which create those hazards, and (2) to obtain information upon which methods for controlling indoor air pollution - thus mitigating adverse health effects - can be based. The achievement of these objectives requires the development of models which can describe and account for the observed changes in the parameters of the interactions of indoor air pollution with individuals and with the indoor environment.

Such models may be simple, qualitative descriptions of interactions between a few elements of the indoor air pollution problem; or they may be complex, mathematical descriptions, involving many parameters. All models, to be useful in understanding the problem, have two common attributes: they simplify complex situations by imposing a pattern and a limited number of categories upon a set of facts, and they have a predictive capability. With a model one can say that given a defined set of circumstances (inputs) there can be calculated one or more other associated circumstances (outputs).

A complete mathematical model of the indoor air pollution problem would enable a researcher, given appropriate input information about air pollution sources and other factors, to calculate health hazards in any indoor environment. Some of the input data for that model would be extremely difficult to obtain. With the present inadequate state of knowledge of factors affecting indoor air pollution and human health the model's results would be of doubtful validity. The complexity of the model, even with much necessary simplification, would probably make it costly to operate. But despite these problems researchers have considered it desirable to move toward developing such models. Models represent an important key to understanding and correcting the problems of indoor air pollution, as described in Section 9.0 of the main text of this report.

A model with an output which quantifies the health hazard (or health effect) of one or more air pollutants in an indoor, nonworkplace environment should have the following major classes of inputs:

- Ambient outdoor air pollution
- Climatology and meteorology
- Building design and siting elements
- Heating, ventilation and air conditioning characteristics of the building
- Indoor air pollutant sources
- Indoor-outdoor energy flow
- Building occupancy characteristics, including personal habits of the occupants
- Mobility patterns of the occupants within the building over time

- Personal health status characteristics of the occupants
- Toxicity of the pollutants, in terms of dose-response
- Exposure and dosages of air pollutants experienced by the occupants when away from the building
- Costs associated with all parameters.

No such general model exists, although several efforts to design indoor pollution exposure models, having much of this input, are now in the planning stages. A large model of this kind, when created, will operate through the joining together of less ambitious models which seek to describe and quantify subsets of the major elements.

There is an important existing body of research in the modeling of a subset of the first five factors listed above (ambient outdoor air pollution, meteorological parameters, building design parameters, the building heating and ventilation system, and indoor pollution sources) to produce information about indoor pollution concentrations. These models are called "indoor-outdoor" models. Five such models, of increasing complexity are discussed subsequently. The simplest of these endeavor only to describe and quantify indoor-outdoor air exchange rates, but such quantification is an essential element of any effort to relate indoor to outdoor air pollution concentration levels.

The recent emergance of a new concern in the United States for energy conservation has led to an increased interest in reducing energy losses from buildings, and in creating new building design standards which reduce the rate of indoor-outdoor air exchange in buildings - thus retaining heated or cooled air within the building and minimizing energy loss. The indoor-outdoor relation of air pollutants are also altered by these measures.

Models which endeavor to define energy flow-air exchange-structure-meteorology relationships in buildings are thus also of potential interest and use in defining indoor-outdoor air pollution relationships and indoor air pollution levels. Such models are also discussed in the text which follows.

In summary, it can be observed that indoor air pollution models - either in their ultimate full form of exposure-dosage-response models or in the limited form of indoor-outdoor air pollution concentration models - may be valuable tools for the health planner, the building designer and the air quality planner. These models can assist the planner to decide where and in what quantitative manner he should intervene in the indoor air pollution problem to limit the adverse health effects of indoor air pollution while optimizing energy conservation and costs.

Against this background the present report reviews the literature of analytical modeling studies of indoor-outdoor air pollution relationships. Specifically examined is the state of the art of definition of the following model parameters: pollutant source strengths, decay rates, indoor environmental parameters, structure identification parameters, and the impact of human activity. Following the review of the state of the art, as exemplified by descriptions of modeling work of previous researchers, there is a discussion of the elements of a new model development program which is now underway at GEOMET.

A cautionary note is in order. The discussions which follow are not solely a literature review. To some extent they are also expository, endeavoring to set out basic principles of air flow and modeling, leading to the description of some new concepts for indoor-outdoor air pollution modeling. The text is at times quite detailed, presenting mathematical descriptions which will probably be of interest only to modelers. This material is included for its value to those who will work in the future upon the improvement of existing models. Readers who do not expect to work with details of the modeling process will find this material of lesser interest; for them it is surely not obligatory reading.

A.2 SIMULATION MODELS

This section is divided into three segments: the first segment provides a brief summary of models and computer programs available for calculating energy loads and consumption; the second segment reviews numerical simulation of infiltration and indoor air movement; and the third segment reviews five models which relate indoor-outdoor air pollution levels. The energy consumption models do not directly address the relations between indoor air pollution and energy conservation, but they do speak to the general question of relating energy consumption measurements to ventilation and infiltration rates and to indoor-outdoor meteorology. The discussion of numerical simulation of infiltration and indoor air movement is relevant as an introduction to the problem of indoor-outdoor pollution modeling, which is addressed in the third segment.

A.2.1 Energy Load and Consumption Models

There are numerous computer programs available for calculating energy loads and consumption for the heating, ventilating, and air conditioning of buildings. These energy models differ widely in methodology, input requirements, and resulting output form. Table A-1, on the eight following pages, includes brief descriptions of some of these programs which contain either a detailed load analysis program or a comprehensive system simulation program.

TABLE [illegible]. ENERGY MODELS – METHODOLOGY – INPUTS – OUTPUTS

Model (Code Name)	Input Requirements	Model Outputs	Date-Status Developer	Descriptive Comments
APEC Heating - Cooling Calculation Program, Version [illegible] (HCC)	Building description, weather data, solar radiation data, room-by-room description and systems description.	Room loads and cfm values, zone loads and cfm values, system analysis results, building peak refrigeration and heating load. Optional output for cooling load analysis for 12 hours of a design day.	Completed 1972, revised 1975. Automated Procedures for Engineering Consultants (APEC), Dayton, Ohio	The program calculates design heating and cooling load utilizing ASHRAE methodology. The room is the basic level of calculation for which the requisite design data is specified. Heating load calculations consist of conventional transmission loss analyses involving areas, U factors, and temperature differences. Infiltration is calculated on an input or [illegible] factor basis. The maximum glass solar heat gain for the specified winter month is calculated and its effect on the heat loss for the room is determined along with lighting and occupant heat gain. Cooling load calculations are made on an hourly basis over a 24-hour period for the selected design day, and radiant load components are time-averaged in accordance with the building mass. Glass loads are separated into transmission and solar components, taking into account the glazing material and shading devices. Hourly room loads and cfm values are accumulated and analyzed psychrometrically and peak loads on equipment are determined. Computer language: Fortran IV.
Building Load Estimating Software System (E20-II)	Summer and winter design conditions, building design parameters, room exposure data, room floor, glass, wall, and roof types.	For the entire building and each room: month and hour of peak cooling and the cooling load cfm, and air changes at the peak. Winter heating load for each room.	Operating; [illegible], [illegible] Inc., Grand Rapids, Michigan	The conversational type program calculates cooling loads for each hour for every summer month and the heating load at the winter design condition. The method of calculation used is described in the Carrier Air Conditioning Design Manual. The conversational mode enables the user to correct input errors as they occur and to vary input parameters repeatedly to suit the requirements. Fortran IV is used.

(Continued)

TABLE A-1. ENERGY MODELS – METHODOLOGY – INPUTS – OUTPUTS (Continued)

Model (Code Name)	Input Requirements	Model Outputs	Date–Status Developer	Descriptive Comments
Deere and Co. Load Calculation Program (ABCLN)	Input follows requirements of "Carrier Load Estimating Guide." Also needed: lighting schedule, sensible load schedule, occupancy, coil position relative to fan, ceiling return air plenum.	Output follows format of Carrier Load Estimating Guide; additionally it includes temperature (return air, mixed air, entering and leaving coil, leaving fan), apparatus dew point, air changes per hour, [illegible] per ton, square feet of floor space per ton, percent outside air, flow-load profile, heat loss estimates.	Operating; E. Davis Deere and Company Moline, Ill.	ABCLN calculates air conditioning total building cooling and heating loads, time of maximum loading, and supply air quantity and temperature requirements. The program uses data found in the "Carrier Load Estimating Guide." Fortran IV is used.
Deere and Co. Zone Load Estimation Program (ZONEST)	Input follows the "Carrier Load Estimating Guide." Additionally it requires number of zone's, temperatures of hot and cold deck in heating and cooling seasons, system type (dual duct, reheat, etc.)	Zone load, cfm, air change summaries, dual duct system design and analysis, reheat system design summary.	Operating; E. Davis Deere and Company Moline, Ill.	ZONEST is used to design or analyze new or existing air conditioning systems. The program computes the building zone heating and cooling loads and determines the hour and month of occurrence of peak loads in each zone. For system analysis, the program compares actual installed air volumes with design requirements. The program calculates area and volume and assigns supply air based upon a percentage of sensible cooling load. It also computes air quantity per square foot and the rate of air change for each zone. Only sensible heat loads are calculated. Fortran IV is used.

(Continued)

TABLE A-1. ENERGY MODELS – METHODOLOGY – INPUTS – OUTPUTS (Continued)

Model (Code Name)	Input Requirements	Model Outputs	Date-Status Developer	Descriptive Comments
[illegible] Air Conditioning System Cooling and Heating Load Calculations Program ([illegible])	Occupant sensible and latent heat loads, ventilation rate requirements, temperature data, building characteristics.	Room and zone heating/cooling loads and peaks, room and zone cfm's, air changes, temperature fluctuation, percent dehumidified air, motor horsepower, percent outside glass to air conditioned air, net air conditioned square feet.	Operating; [illegible] and Associates, Inc.	The program finds the maximum heating and cooling loads based on design criteria for each room, zone, and building. From this it determines the required amount of air for each area and reheat if necessary. The program is based on methods outlined in the 1967 ASHRAE Handbook of Fundamentals. In addition, the wall and roof gains in the program are based on the sol-air temperature concept and equivalent temperature differential equations. Program is written in Fortran IV.
National Bureau of Standards Load Determination Program (NBSLD)	Building parameters such as wall properties, ceiling and floor properties, window area and location, operating schedules. Weather data from U.S. Weather Bureau tapes.	Hour-by-hour heating or cooling loads and temperatures for each zone for the entire year. Design day data may be examined as an option.	Written in 1972 & continually revised. T. Kusuda – NBS.	NBSLD calculates the hour-by-hour heating and/or cooling load in buildings. The program utilizes the thermal response factor technique for calculating transient heat conduction through walls and roofs. The program also includes a routine which can calculate the "floating" temperature of those rooms with little or no air-conditioning and natural ventilation. Fortran V is used.

(Continued)

TABLE A-1. ENERGY MODELS – METHODOLOGY – INPUTS – OUTPUTS (Continued)

Model (Code Name)	Input Requirements	Model Outputs	Date-Status Developer	Descriptive Comments
Alternate Choice Comparison for Energy Systems (ACCESS)	Weather data, base load description, base load profiles, design heating and cooling load, space type area, zone data, HVAC system description, and output desired.	Energy consumption and demand for each of up to 36 "systems" of the alternative systems. Numerous optional outputs.	Operating; [illegible], [illegible] Volker and [illegible] under contract to the Edison Electric Institute.	ACCESS permits the simultaneous comparison of up to six alternate methods for meeting the energy requirements of a building. The program may be used at various points in the design process. If the structure is still in the conceptual state, the program utilizes routines which approximate the full input information which would normally be available during the later stages of design. The program calculates hourly zone solar and transmission loads for the year (if not input from another program). These loads are utilized along with base energy loads to calculate net zone space conditioning requirements. Terminal system operation is simulated and equipment energy consumption calculated in one of three general subroutines.
Bridgers and Paxton Energy Analysis Program	Building block load analysis using APEC HCC-III program, architectural description of building, weather data, type of system desired, description of desired system operation.	Daily summary of refrigeration and heating loads along with boiler and chiller input. On solar systems, outside temperature, storage tank temperature, solar collector efficiencies, heat collected by solar system for each 3-hour period per day, monthly and yearly totals of heating and cooling loads and corresponding energy requirements.	Operating; Dale R. [illegible] Bridgers and Paxton Consulting Engineers, Inc.	The program calculates the yearly energy consumption for heating and cooling buildings. HVAC systems presently considered include conventional dual duct system, conventional single zone system, internal heat recovery heat pump system, solar assisted heat pump system, and solar heating and cooling system. Building heating and cooling loads are determined using 3-hour weather data available from the U.S. Department of Commerce National Climatic Center. System simulation is performed, calculating building refrigeration and heating loads. For solar systems, a building heat balance is performed. Performance of storage tank and solar collector systems is simulated and its overall effect on building heating and refrigerating load is determined for each 3-hour period of the day. Program written for IBM 1130 with 8K core.

(Continued)

TABLE A-1. ENERGY MODELS – METHODOLOGY – INPUTS – OUTPUTS (Continued)

Model (Code Name)	Input Requirements	Model Outputs	Date-Status Developer	Descriptive Comments
Energy Conservation Utilizing Better Engineering (ECUBE)	Maximum value and hourly percentage profiles for internal heat gain, electrical load and process load transmission and outside air loads as a function of ambient temperature. Maximum solar loss on the building. Hourly weather data. Heating value of fuel. Part load equipment performance characteristics. Capital cost differential for alternative systems, salvage values, maintenance costs.	Monthly, annual and peak energy requirements. Annual fuel requirements for alternative systems. Cash flow and discounted rate of return on alternative investments.	Available in 1975. Continually updated. American Gas Association.	The ECUBE series of programs utilizes design point calculations of peak thermal and electrical loads to make hourly, monthly, and annual estimates of the energy requirements of a building. The energy consumption of various types of systems which may be used to meet these requirements are then calculated and the program compares the total owning and operating costs of the various systems being considered. The program series consists of three basic computer programs: (1) Energy Requirements Program, (2) Equipment Selection and Energy Consumption Program, and (3) Economic Comparison Program.
Honeywell Total Building Simulation ([illegible])	Building material descriptions, building descriptions, weather data, mechanical sys., st., operating modes.	Load on interior and exterior zones and the systems, energy requirements to maintain operating conditions, zone temperatures, etc. – hourly, for demand and load profiles.	Written in January, 1975, Operating. [illegible], Honeywell, Inc.	The program incorporates the building envelope, mechanical systems, and the dynamics of the control systems to provide a "true" picture of energy requirements and temperature distribution in the building. The program takes into consideration the dynamic characteristics of the building material, heat storage, and time constants of mechanical systems and controls. The program provides a detailed output (every minute), or integrated output for hourly, daily, monthly, and annual summary of energy consumption. Computer language used is Fortran IV.

(Continued)

TABLE A-1. ENERGY MODELS – METHODOLOGY – INPUTS – OUTPUTS (Continued)

Model (Code Name)	Input Requirements	Model Outputs	Data Status Developer	Descriptive Comments
McDonnell Douglas Automation Company's Annual Consumption of Energy Program (MACE)	Weather specifications, building and system descriptions, modes for which calculations are to be made, energy rate structures, master time schedules and appropriate loads (such as occupants, lights, appliances, etc.)	Hourly space and building loads, electrical usage, fuel consumption, and cost of carbon hourly (?) and monthly and yearly total of each.	Operating: McDonnell Douglas Automation Company	MACE uses methods recommended by ASHRAE whenever possible. The load calculation section utilizes methods outlined in Proposed Procedures for Determining Heating and Cooling Loads for Energy Calculations, ASHRAE 1969. These methods include the use of thermal response factors for calculation of the transient heat transfer through roofs and walls. The component and system simulation section uses procedures outlined in Proposed Procedures for Simulating the Performance of Components and Systems for Energy Calculations, ASHRAE, 1969. The economic section uses the local prevailing utility rates, which are input into the program by the user. The U.S. Weather Bureau is the source of the following hourly weather variables: dry and wet bulb temperatures, wind velocity and direction, cloud cover, cloud type, and barometric pressure. MACE will accept sources of weather data, once they have been prepared in the proper format.
Meriwether Energy Systems Analysis Series	Engineering design data, descriptions of system design and operation, weather data, utility rate structure, owning and operating cost and financial data.	Monthly and annual demand and consumption of energy for systems and equipment, monthly and annual utility costs, life cycle and cash flow analysis.	Operating: Ross F. Meriwether and Associates, Inc. San Antonio, Texas	The Energy Systems Analysis Series is a library of computer programs which determine the annual energy consumption of various types of systems and equipment for a typical year of operation, and determine the relationship between these energy costs and other owning and operating costs. The programs normally used in conducting an energy analysis consist of the Energy Requirements Estimate (ERE) which calculates the hour-by-hour thermal and electrical loads for a building, the Equipment Energy Consumption (EEC) which simulates the operation of the various pieces of equipment, and the Economic Comparison of Systems (ECS) which calculates the total owning and operating cost of each system. A number of auxiliary programs are available to complement the basic analysis series.

(Continued)

TABLE 5-2. ENERGY MODELS — METHODOLOGY — INPUTS — OUTPUTS (Continued)

Model (Code Name)	Input Requirements	Model Outputs	[illegible] Developer	Description Comments
NASA's Energy Cost Analysis Program (NECAP)	Building parameters, building coordinate system, azimuth angle, pattern descriptions and tilt angle, floor, ceiling, furnishing data, space description, fuel rate schedules, type of energy distribution system and pertinent parameters, cost information.	Response factors (if requested), summary of design weather, space and building loads, surface shadow patterns and shadow calculations, environmental space heat extraction and addition rates, variable temperature loads (if requested), [illegible] summary of loads on fuel, equipment capacity, [illegible], monthly, and annual energy summary.	Consultant [illegible], Inc., under contract to the National Aeronautics and Space Administration, Langley Research Center.	The NECAP program follows the procedures outlined in the ASHRAE booklet "Procedures for Determining Heating and Cooling Loads for Energy Calculations" to estimate the energy requirements for buildings. The program is actually a set of six individual computer programs including (1) a Response Factor program (2) a Data Verification program (3) a Thermal Loads Analysis program (4) a Variable Temperature program (5) a System and Equipment Simulation program and (6) an Owning and Operating Cost program. Standard wall construction and schedules can be used to simplify program input. The program is an extension of the Energy Utilization Program developed for the U.S. Postal Service, but incorporates extensive modification to improve its usability including completely revised documentation.
Program for Analysis of Energy Utilization in Postal Facilities	Geometry of building and its surroundings, thermal and physical properties of walls and wall constructions, operating schedules, weather data, fuel system characteristics, [illegible] operating [illegible], and types of heating-cooling combinations to be examined.	Hour-by-hour sensible load, latent load, return air lighting load, lighting equipment and power consumption are summarized. Optional output includes shadow patterns for various building surfaces at the hour desired.	General American Research Division of General American Transportation Corporation.	The program (often known as The Post Office Program), calculates the energy requirements for heating and cooling of buildings via a two-step calculation procedure. First, the hour-by-hour heating and cooling load is calculated utilizing the thermal response factor technique. The system simulation portion then calculates the energy required by the HVAC system to satisfy the imposed thermal loads. An economic analysis program can then be used to compare annual owning and operating costs of various combinations of heating and cooling plants. Fortran is used.

(Continued)

TABLE [illegible]. ENERGY MODELS – METHODOLOGY – INPUTS – OUTPUTS (Concluded)

Model (Code Name)	Input Requirements	Model Outputs	[illegible] Developer	Descriptive Comments
[illegible] Program for Facilities HVAC Design and Energy Analysis ([illegible])	Building construction and orientation parameters, surface data, optional shadow data, space data, thermostat schedules, people load data, optional overlay specified [illegible], types of energy, distribution and conversion systems, and equipment cost information.	Space and building peak loads broken out into components, optional surface and space response factors, [illegible] weather [illegible] shadow pictures and calculations, recommended space air flows and heat extraction and addition rates, equipment capacity summary, summary of space and system loads [illegible], monthly and annual energy summary, space temperature and part load [illegible], economic comparison of alternatives.	Available since January, 197[illegible], [illegible], Inc.	The [illegible] program follows procedures outlined in the ASHRAE booklets "Procedures for Determining Heating and Cooling Loads for Energy Calculations" and "Procedures for Simulating the Performance of Components and Systems for Energy Calculations" to estimate the energy requirements for buildings. [illegible] is an extension of NASA's Energy Cost Analysis Program (NECAP), but incorporates complete data verification, full set of self-instructional input forms, [illegible] system simulations, plus packaged systems and heat recovery devices, and complete internal restructuring resulting in reduced core requirements and reduced running times.
Trane Air Conditioning Economics (TRACE)	Building, system, and equipment description. Economic factors.	Peak building loads, building and equipment hourly and monthly energy consumption. Economic comparison of life cycle cost for up to four alternatives in one computer run.	First available in 1972, continually updated. [illegible] at the Trane Company.	The program calculates peak and hourly zone loads based on coincident hourly climatic data for temperature, solar radiation, wind and humidity of typical days in the year representing seasonal variations. The average days are compiled based on the most recent ten years of U.S. Weather Bureau data. The design phase then receives input from the load phase as well as system type information and new design information and calculates supply air quantities and temperatures. The system simulation phase utilizes hourly zone loads and calculates return air quantities and temperatures and accounts for system loads such as reheat loads. The equipment simulation phase takes the hourly output from the system simulation phase and calculates the annual energy consumption based on part load performance data which is available on tape. The economic phase then does an economic comparison of the various design alternatives based on input consisting of energy consumption data, utility rate structures, and expected installation and maintenance costs.

A.2.1 Numerical Simulation of Infiltration and Indoor Air Movement

Infiltration Simulation

Although there are varying degrees of sophistication in the methods by which total heating and cooling loads are computed by the models listed in Table A-1, the portion of the total load resulting from transfer of heat by air exchange between indoors and outdoors is usually calculated by a method which simply assigns an air change rate for computation based on building and occupancy type. The majority of the energy consumption models utilize this simple procedure despite considerably more complex modeling for other contributing loads. Three of the more sophisticated models, NBSLD, NECAP and BEAM, utilize optional infiltration or ventilation methods. In addition to the option of using the standard air change approach, NECAP also provides the option of using the crack length method. The NBSLD model provides for the option of using the Achenbach-Coblentz infiltration correlation method. The BEAM program provides the versatility of using any of the three methods; air change, crack length, or Achenbach-Coblentz correlation; see equation (1) below.

The crack length method goes one step beyond a simple air change approach and computes infiltration rates as a function of building opening sizes and types, including windows, doors, and vents. The accuracy of this method is dependent upon precise description of the building openings.

The Achenbach-Coblentz method utilizes a wind speed and temperature correlation for estimating infiltration rates. The correlation is of the form

$$I = A + BV + C|\Delta T| \qquad (1)$$

where:

I = Infiltration rate in air changes per unit time

V = Wind speed

T = Temperature difference between the interior of the building and the outside

and A, B, and C are constants characteristic of the building being analyzed. Under zero wind and temperature difference conditions the Achenbach-Coblentz correlation reduces to the constant A. This represents a constant infiltration term due to opening and closing of doors and windows, the operation of various fans, and possibly other unidentified infiltration mechanisms.

The infiltration due to wind is governed by the constant B in the correlation. The coefficient represents the results of an air flow balance of individual flow paths across windows, doors, and walls.

In the absence of wind, fan operation, door opening and closing, and combustion air requirements, there remains another driving force for inducing infiltration. Temperature differences between the interior and exterior of a residence produce different air density gradients with altitude. The phenomenon is known as the chimney or stack effect. In the winter, for example, the stack effect produces a higher pressure outside than inside at the lower levels of a residence. The reverse is true for the upper levels. In most cases, a neutral zone exists somewhere between the upper and lower levels, where the net pressure difference is zero. The net result for the winter is that the outside air flows in through the crackage in the lower section of the house and the warm inside air escapes through the upper section openings. Reverse flow conditions occur during the summer. The Achenbach-Coblentz correlation takes this into account through the $C|\Delta T|$ term.

Indoor Air Movement Simulation

None of the infiltration calculation routines, as used within available energy conservation models, are capable of accurately describing infiltration and ventilation flows within the building itself. These routines are chiefly concerned with the heating and cooling loads due to the flow of outside air into the buildings. There are, however, ventilation models which are basically air movement simulation models, concerned with accurate description of air flow patterns within structures. Three such programs, the Residential Infiltration Program (RIP), the National Research Council of Canada program (NRC), and the Air Movement Simulation Program of NBS, are described below:

1. The RIP infiltration program evaluates individual contributors to the overall infiltration rate within residential buildings. The computer program performs a flow balance on a given residence. The residence is specified in terms of window, window frame, door, and wall characteristics. In addition to the component type, size, and number specification, the program can be supplied with steady state positive or negative exhaust rates. This aspect permits the simulation of exhaust

fans, furnace operation, and positive pressurization which may be used for the purpose of eliminating infiltration. The external environment is specified in terms of wind speed and direction.

The program uses the wind speed to compute the stagnation pressure and then applies a cosine distribution of pressure, on the basis of the relative angle between the wind direction and the plane of the wall, to compute the pressure on the outside surface of each wall. These pressures, in conjunction with a flow equation, are used to solve for the unknown internal pressure using iteration methods. Once the inside pressure is determined, the program evaluates the flow rates across each component as well as the overall infiltration rate.

II. The primary objective in development of the NRC computer program was to study the smoke movements in the buildings in the case of fire. This program has been utilized to develop correlations between infiltration rate through buildings as a function of ambient temperature, wind velocity, and wind direction. The mathematical model of this program is represented by a set of compartments stacked one on top of another and by a set of shafts that pass through all the compartments. Leakage openings are present in each outside wall of each compartment and in all the floors and shaft walls so that air can pass from every compartment to adjacent compartments and to each of the vertical shafts. Each compartment may represent one story of the building, or may represent a number of stories in order to save computation costs. Each shaft may have two vents to the outside. Vent openings are designated "top" and "bottom," but they may be located at any level. The effects of the air handling systems are accounted for by specifying the net quantity of air supplied to each vertical shaft and to each compartment. Stack effect (see discussion under Infiltration Simulation above) is calculated for any given outdoor temperature.

The flow equation used is

$$F = EA\ (\Delta P)^{x} \qquad (2)$$

where

F = flow rate through a leakage opening (cfm)
EA = flow coefficient (cfm/in^2)
ΔP = pressure differential (in*)
x = flow exponent ($0.5 \le x \le 1.0$).

In order to account for the effects of wind, the pressures due to wind on each face of the building at each level must be determined. The developers of the NRC program recommended that this be done by specifying a matrix of wind pressure coefficients which relate the wind pressures at each level to the ambient wind velocity pressure, based on the wind speed at a height of 30 ft as measured by a meteorological station. A more realistic vertical profile of wind speed and directions, introducing a vertical wind speed gradient and turning, could be introduced into the matrix if desired and if data are available. These wind pressure coefficients account for wind velocity profile, ground effect, and shading effect by other buildings. Coefficients could be obtained from wind tunnel tests on a model of the building. Wind pressure coefficients for each level and for 16 directions must be specified with the other data.

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* Inch of water 4°C equivalent to 5.210/ft^2, which is the pressure of one-inch head of water.

The following assumptions made by NRC constrain the model:

- Frictional resistance of vertical shafts is neglected
- Net air supplied by the air handling systems is assumed to be constant and independent of building pressures
- The building has an open floor plan with no provision for separate rooms or vestibules
- Pressures, flows and leakage openings are assumed to occur at mid-height of each level
- Temperature inside compartments and shafts is assumed to be 75°F.

The flow balance equations for each compartment and each shaft are:

for the ith compartment,

$$\sum_{k=1}^{4} F_{o(i,k)} + F_{b(i)} - F_{a(i)} - \sum_{j=1}^{JJ} F_{s(i,j)} + F_{ac(i)} = 0$$

and for the jth shaft, (3)

$$\sum_{i=1}^{NN} F_{s(i,j)} + F_{bv(j)} + F_{tv(j)} + F_{sh(j)} = 0$$

where

$F_{o(i,k)}$ = flow from outside through side (k) to compartment (i)

$F_{b(i)}$ = flow from compartment below to compartment (i)

$F_{a(i)}$ = flow from compartment (i) to compartment above

$F_{s(i,j)}$ = flow from compartment (i) to shaft (j)

$F_{ac(i)}$ = net flow of air supplied to compartment (i) by air handling system

$F_{bv(j)}$ = flow into shaft (j) through bottom vent

$F_{tv(j)}$ = flow into shaft (j) through top vent

$F_{sh(j)}$ = net flow of outside air supplied into shaft (j) by air handling system

NN = number of compartments

JJ = number of shafts.

Combination of mass balance Equations (3) and (4) with flow Equation (2) results in a set of simultaneous non-linear equations. The outside pressures and the pressure differences due to column weight may be calculated from the input data.

These simultaneous non-linear equations are solved by a method of successive linear approximations. The non-linear function described by Equation (2) is shown in Figure A-1. In the region near point ($\Delta P_t, F_t$) this function may be approximated by a straight line which is tangent to the curve at this point. The equation of this linear function is

$$F = K' \quad \Delta P - \Delta P_t \qquad (4)$$

where

$$K' = K \; n \; \Delta P_t^{\,n-1}$$

and

$$\Delta P_i = \Delta P_t - \frac{F_t}{K'}$$

Each leakage flow in Equations (3) and (4) may be expressed by this type of linear approximation. The resulting set of NN + JJ linear equations for the pressures can then be solved by standard methods.

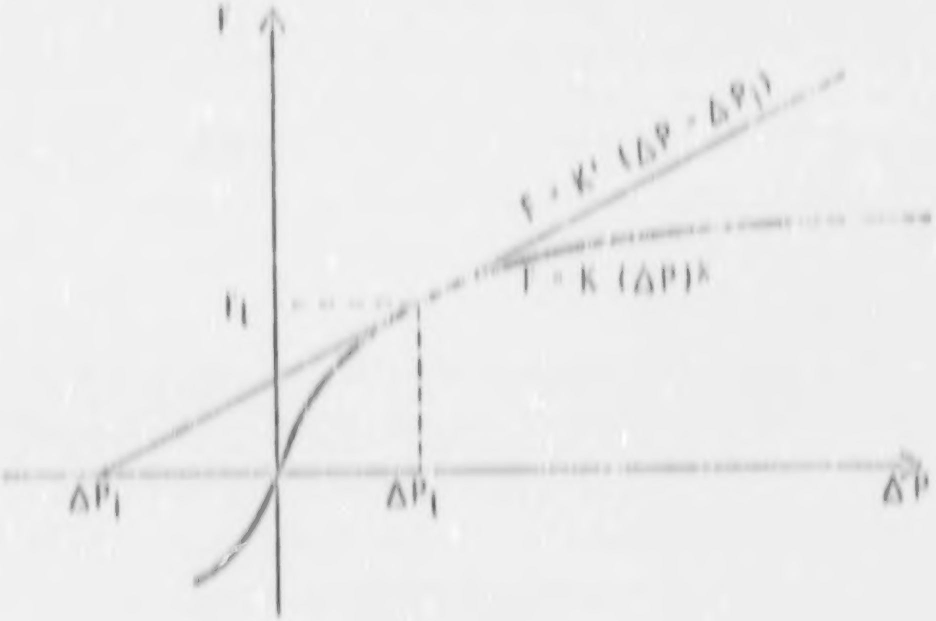

Figure A-1. Linear approximation of flow equation.

The iteration method is as follows: an initial linear approximation is made for each flow and the resulting equations are solved for space and shaft pressures. The flows corresponding to these pressures are then calculated, and the flow through each element is compared with the flow used for linearization of that element. If the difference is greater than the convergence criterion (a criterion supplied by a variable "error" in a special subroutine which for this work has the value of 0.1 cfm) that element is re-linearized about the most recently determined flow and the linear simultaneous equations are solved again. This procedure is repeated until the flow through every element satisfies the convergence criterion.

III. NBS Air Movement Simulation Program

This modeling program was developed by Integrated Systems, Inc., for the National Bureau of Standards for the purpose of studying smoke patterns within buildings. The program, which simulates vertical and horizontal air flow patterns inside a building, is the most comprehensive air movement simulation model presently available. It is described in considerable detail in the following pages because its description will provide the interested reader with an opportunity to understand basic principles alluded to in briefer descriptions of other models in this chapter. A careful review of this model will also demonstrate the difficulty of reducing the complex behavior of indoor air movement to manageable parameters for modeling.

The primary design goals of this NBS program are to achieve a realistic representation of building spaces and HVAC (heating, ventilation and air conditioning) systems, and to achieve realistic flow relationships in the simulations. The design of that part of the computer program which simulates air movement is based upon an already existing preliminary design. The new elements in the NBS program are principally the detailed logic necessary for handling large quantities of data and the numerical analysis necessary to achieve solutions.

The major problem with earlier air movement simulation models had been the lack of realistic modeling ability for the spatial configurations of buildings and of the components and configurations of HVAC systems. The design utilized in the NBS program has the following descriptive capability:

1. Up to 100 floors of a building
2. A single corridor on each floor
3. Up to 10 compartments on each floor, which can be related to zones, suites, or specific spaces
4. Up to 25 HVAC systems, each composed of:
    a. An air handling unit (AHU) (blower/fan) which delivers air to the supply duct network
    b. A supply duct network
    c. A return air duct network or plenum
    d. An outside air supply shaft or duct to the AHU inlet
    e. A return air coupling to the AHU inlet to supply recycled air

   f. A means to provide any mixture of outside air (OA) or return air (RA), from 100-percent OA to 100-percent RA, to the AHU

   g. A ventilation shaft or duct to exhaust return air not recycled

   h. An exhaust fan for the ventilation shafts.

5. Up to 20 different fans/blowers for use anywhere in the building/HVAC system

6. Up to 90 shafts or ducts made up of any combinations of the following, except as indicated:

   a. Elevator shafts to a maximum of 16

   b. Stairwells

   c. Air supply ducts/shafts

   d. Ventilation ducts/shafts

   e. Cable/pipe/duct shafts

   f. Window HVAC unit pipe shafts.

7. Up to 70 sets of non-fan/blower coupling parameters

8. Up to 10 external wind functions which are linearly variable as a function of height

9. Up to 20 single temperature values for spatial temperature specification and 20 temperature-height functions for shaft/duct temperature specification.

Other features of a building which can be described in the program include:

1. Inlet fans/blowers to pressurize shafts, such as stairwells

2. HVAC air supply to stairwells

3. External leakage to:

   a. Corridors

   b. Compartments

    c. Stairwells, to a maximum of 20
    d. HVAC window unit shafts
4. Ventilation fans from corridors and compartments to ventilation shafts and directly to the outside
5. Outlet fans from the various forms of shafts.

Although all characteristics of all building HVAC systems cannot be specifically represented by the capability of the computer program developed, the functional representation of almost all characteristics can be modeled by appropriate use of the available characteristics.

In the development of the NBS program it was initially planned that the basic numerical solution of the program would be obtained by the use of linear simultaneous equations and a linearizing technique for non-linear equations. There are 1,265 possible non-linear equations in the program. This large number of equations, together with the variability and number of allowable boundary conditions, and the variability of the forms which arbitrary equilibrium equations may take, combine to create a very difficult problem for such an approach. To obtain solutions, it would be necessary to develop a computer subroutine to generate the elements of the coefficient matrix. It would also be necessary to develop a subroutine operating on the generated, square matrix to reduce it to some form that can be easily treated within a computer memory, such as a band or triangular matrix. Past experience in developing such computer programs for highly variable systems, which had regular and symmetric matrix properties (as compared to the skewed matrices which would characterize the NBS program) and regular and well-behaved boundary condition definitions, indicated that such an undertaking was not feasible within the time and resources available. Consequently, this approach was abandoned and another sought.

The method subsequently chosen for the solution of the NBS Air Movement Simulation Program was the use of nested, iterative solutions. The method is straightforward, allowing relatively easy handling of the data. The nested, iteration approach is usually more costly in computer time required than is the matrix approach, but this would not be the case with the angular skew inherent in the NBS program.

Two other factors weighed heavily in favor of the nested iterative approach. One factor was the certainty of fitting the computer program into normal and readily available computer memory partitions, whereas a great deal of doubt existed with the linear system approach. At the least, special treatment of the memory space or the data (e.g., temporary storage on auxiliary memory devices) would have been required. The second factor was that the use of matrix inversion techniques frequently leads to no useable results emanating from the computer output when highly skewed angular systems are encountered. In the case of the nested iterative approach, useable data can be obtained even though exact solutions (i.e., satisfaction of the convergence criteria) are not achieved.

The fundamental basis of the NBS computer program simulation of the steady-state air movement in a building/HVAC system is the mass flow rate equilibrium equation; i.e., for a given building space or HVAC component, denoted by the index, j,

$$F_{1j} + F_{2j} + \ldots + F_{ij} + \ldots + F_{nj} = 0, \qquad (5)$$

where F_{ij} is the mass flow rate of air between the i^{th} and j^{th} building spaces and HVAC components.

This equation is solved for each corridor and compartment on each floor, for each shaft, for each supply duct network, for each return air duct network, and for each AHU. The system of equations that must be solved in each case is completely dependent upon the building HVAC system modeled by a user from these available components and the imposed conditions provided.

The mass flow rates between any two building HVAC components are based upon the type of passage between any two components, i.e., large, moderate, or very small (crack). In the case of a large opening, such as an open doorway, a vent or register, etc., the mass flow rate is determined from Bernoulli's steady-state equation, with some head loss, i.e.,

$$F = kA\sqrt{2g\rho\Delta P} \qquad (6)$$

where

A is the effective opening area (ft^2)

k is the flow coefficient, ranging between 0.6 and 1.0

ρ is the density of air of the inlet side (lb/ft^3)

and

ΔP is the pressure difference between the two components or across the opening (lb/ft^2).

For moderate openings, such as under a door, around an elevator door, etc., the same form of Equations (5) and (6) is used as for the large openings. However, a contraction coefficient (due to contraction of flow) and an approach factor have been combined into a single coefficient, k, which is a function of geometry and Reynolds number. In this case, the coefficient k ranges between 0.2 and 0.3.

For very small openings or cracks, such as are found around windows, it was assumed that the mass flow rate could be expressed as

$$F = C\,\Delta P^{n} \qquad (7)$$

where

n is the flow exponent, between 0.5 and 1.0

and

C is the flow equation.

It was also assumed that the flow through such passages would obey Darcy's law (7). Hence,

$$n = 1$$

For simplicity, the above three forms of expressing mass flow rate for different openings were reduced to a general form, sometimes referred to as the orifice equation, i.e.,

$$F = k\,\rho^{x}\,\mu^{1-2x}\,\Delta P^{x} \qquad (8)$$

where

k is determined as a function of the type of opening, the effective area, and the appropriate flow coefficient for the above types of openings

x is 0.5 for the large and moderate openings and 1 for the very small or crack-type opening

and

ρ and ΔP, as defined above, and μ are the viscosity of air on the inlet side of the opening.

The program was designed to allow a user to specify k and x or the effective area A and the type of opening. If the latter option is utilized, the flow coefficients are determined as follows:

1. For a large opening

   $k = 0.8$

2. For a moderate opening

   $k = 0.25$

3. For a very small opening or a crack

   $k = 0.1$

External wind leakage can be a significant factor in the effectiveness of an HVAC system and, under certain conditions, can defeat the use of an HVAC system in controlling pressures within a building. Consequently, significant capability is provided to define varying external conditions operating on the external walls of the simulated building. As indicated, 10 external wind states were included in the design of the computer program. Each of these states was then defined as wind speed, normal to the wall, varying with height, and at a given temperature. Temperature was held constant for each wind state, i.e.,

$$V = f(h_i) \tag{9}$$

where

$f(h_i, T)$ is a tabular function

and

h_i is the height at the i^{th} point.

Excluding an exhaust fan or intake blower interfacing directly with the outside air, all of the air flow in or out of the simulated building is determined as a function of the pressure difference. Consequently, the pressure due to the wind at any given floor level and on any given external wall must be determined. The dynamic pressure due to the wind is defined as

$$P_d = 1/2 \rho V^2 \tag{10}$$

where

P_d is the dynamic wind pressure (lb/ft^2)

ρ is the density of the outside air at the given height and temperature (lb/ft^3)

and

V is the wind speed at the given height on the given external wall (fps).

Critical to a realistic simulation is the representation of the behavior of air within an open shaft, such as a stairwell, elevator shaft, or plumbing chase. Two basic situations are usually encountered with such shafts: (1) a non-pressurized shaft which is coupled for air movement purposes by leak passages, and (2) a pressurized shaft with specific and designed flow openings as well as leakage openings.

The basic approach to the solution of the equilibrium condition within a shaft was based upon an automated selection of the most significant flow point to control the solution at the convergence pressure. Continuity was maintained by calculating the pressures at all other floor levels as a function of height, positive or negative, from the reference, or convergence, pressure.

In general, the upward or downward recursion relationship utilized was expressed as

$$P_i = P_{i+1} + (h_{i+1} - h_i) \frac{(\rho_i + \rho_{i+1})}{2} \qquad (11)$$

where

P_i is the pressure of the mid-height of i^{th} floor level

P_{i+1} is the pressure of the mid-height of the $i+1^{th}$ floor level

h_i is the mid-height of the i^{th} floor level

h_{i+1} is the mid-height of the $i+1^{th}$ floor level

ρ_i is the density of the mid-height of the i^{th} floor level

and

ρ_{i+1} is the density of the mid-height of the $i+1^{th}$ floor level.

Since density is a function of pressure and temperature and these two variables can vary with height, it is necessary to solve the above expression for pressure, both for the upward and downward cases, by substitution of the density relation into the equation.

The continuity condition and the equilibrium condition are solved simultaneously to determine the pressures within an unpressurized shaft.

In the second case, i.e., where an inlet blower existed and a pressurized condition existed, another relationship was introduced to include the effects of the blower or fan pressurization. The duct equation is introduced to provide a means of determining the vertical pressure distribution within a pressurized shaft, i.e.,

$$\Delta P_{IO} = \frac{0.0533\ \overline{T}\ F_O^2\ |\Delta h|}{\left(\frac{\overline{A}}{0.7854}\right)^{5/2}\ \overline{P}_{IO}\ |} \qquad (12)$$

where

ΔP_{IO} is the pressure loss between the fan inlet to the shaft and the major outlet (PSF)

$\overline{T}$ is the average temperature between the shaft's inlet and outlet (°R)

Δh is the distance between the shaft's inlet and outlet (ft). (In the case of a stairwell, a spiraling factor is included.)

$\bar{A}$	is the average cross-sectional area of the shaft between the inlet and the outlet (ft^2)
$\bar{P}_{10}$	is the average pressure in the shaft between the inlet and the outlet (PSF)

and

F_0	is the mass flow rate at the shaft outlet (lb/min).

The duct loss equation is solved as an implicit function iteratively,

where

$$F_0 = \phi(P_0, P_{ext}) \tag{13}$$

$$\bar{P}_{10} = \psi(P_0, P_1) \tag{14}$$

and

P_0	is the pressure at the outlet
P_{ext}	is the pressure on the external side of the outlet
P_1	is the pressure in the shaft at the inlet.

The loss is assumed to occur between the inlet point and the outlet point, where either one could be above or below the other. The loss distance is assumed to be the distance between these two locations, except in the case of a stairwell. In the case of a stairwell, a lengthened channel is assumed, due to the spiraling nature of a stairwell, and the vertical distance between the defined inlet and outlet was multipled by a lengthening factor.

The loss in pressure was included in the continuity condition. A linear relationship is used between the inlet and the outlet to provide the vertical distribution of the pressure loss. If a shaft extends beyond an inlet or outlet away from the other, a stagnant condition is assumed, with pressure equal to the inlet or outlet, respectively.

Initially, an attempt was made to represent a fan or blower as a function of typical fan or blower characteristics and the air state at either the inlet or the outlet. However, the conditions were of a variable nature and could not be satisfied with the expressions attempted. As a result, two methods of specifying a fan or blower, both of a simple form, are utilized.

The first method allows a user to specify a blower rotational speed (RPM), horsepower, and an outlet area. From tabular data representing a family of fans/blowers, throughput is determined, i.e., static discharge pressure and volume flow rate at standard conditions.

The second method allows a user to specify the static discharge pressure and the volume flow rate under standard conditions.

In either case, the volume flow rate is converted to mass flow rate; i.e.,

$$F_B = Q_B \rho_S \tag{16}$$

where

F_B is the mass flow rate output of the blower/fan (lb/min)

Q_B is the specified volume flow rate output of the blower/fan (SCFM)

and

ρ_s is the density of air under standard conditions (lb/ft^3).

The mass flow rate from a specified blower enters the equilibrium equations coupled at the blower/fan, except in the case of an outlet or inlet fan or blower, as effectively a boundary condition; i.e., the mass flow rate for that component is fixed and not allowed to vary as a function of the iterative processes.

The given static discharge pressure is of particular importance in the case of pressurized shafts and enters the solution via the duct loss equation in the continuity relationship. In other cases, where the flow only enters the equilibrium condition, the given static pressure is not directly used.

In order to provide as realistic a simulation as possible, particularly with regard to simulating pressure differences, air density was not assumed as constant. Air density is calculated at each point in the programmed process where it was required, as a function of the temperature and pressure of the building space or HVAC component involved in the calculation; i.e., at a constant height,

$$\rho = \frac{0.0187618P}{T} \qquad (16)$$

where

P is the pressure (lb/ft^2)

and

T is the temperature (°R).

Since the air within an open shaft is treated as a continuous medium, i.e., the pressures were determined as a function of the controlling flow, e.g., an inlet blower, and as a function of height, the density becomes appropriately variable as a function of height.

The determination of the viscosity of air is purely a function of temperature. A linear segmented curve fit was made over the range of anticipated temperatures. The representation utilized is as follows:

$$\mu = a + bT \tag{17}$$

where

$a = 3.4 \times 10^{-7}$

$b = 0.006 \times 10^{-7}$

for

$$0 \le T \le 125$$

and

$a = 3.5 \times 10^{-7}$

$b = 0.0052 \times 10^{-7}$

for

$$125 < T \le 250$$

$$\mu \text{ is in lb sec/ft}^2$$

and

T is in °F

The NBS air movement model, and the earlier discussed RIP and NRC models as well as the energy numerical models, which were described in Table A-1, have major thrusts which are not directly related to indoor air quality determination. They have, however, been described here because the concepts developed and used in these models are relevant to the investigation of numerical analysis for indoor-outdoor air pollution models, particularly in that they provide methods for calculating infiltration, exfiltration and ventilation rates which are parameters of great importance in the indoor-outdoor pollution models. In addition, the energy models provide fundamental elements for future efforts to study the optimization of desirable energy consumption measurements and low indoor air pollution levels.

A.2.3 Indoor-Outdoor Air Pollution Models

The subject of relating the outdoor ambient and indoor air pollution levels is relatively recent and research emphasis has been placed on field measurements of air pollution rather than upon the development of numerical models to describe indoor-outdoor air pollution relations. It is not, therefore, surprising that the number of existing models is small. Five models relating indoor and outdoor air pollution levels were identified in the research literature. These are reviewed in following pages. A number of them were developed for purposes other than describing indoor-outdoor air pollution relations in buildings; some of the early work was done in connection with chemical warfare problems. Where necessary, the relevance of these models to the indoor-outdoor air pollution problem in buildings will be stated.

The Effective Residence Time Model

The effective residence time model establishes a functional relationship among the three fundamental parameters of ventilation rate, residence time, and concentration. It has some severely constraining assumptions which limit its application to reality, but it is a useful step toward understanding indoor pollutant dispersion. The theory developed has been formulated independently, and utilized in various projects by Milly [426], Constance [138], Drivas et al. [171], and others.

The model is based upon an equation relating the volume of an enclosed space, air flow between outdoors and indoors, and pollutant concentrations:

$$-Vdc = c\upsilon dt \qquad (18)$$

In this equation V indicates the volume of an enclosure in m^3, υ is the rate of entry or egress of air into the enclosure in m^3/hour, and c is the initial concentration of a pollutant inside the enclosure in mg/m^3. A ventilation rate, appearing in subsequent equations, is defined as $a = \upsilon/V$ air changes per hour. A constraining assumption of the model is that the generation of the pollutant ceases at the instant of measuring its concentration, an assumption which presents difficulty in using this model to simulate realistic behavior of some pollutants in residential enviroments but which was appropriate for many of the military uses for which the model was first developed. It is appropriate for considerations of pollution dispersion from aerosol sprays or from other short-peak pollutant generators. The model assumes that in time dt the pollutant concentration decreases by dc which corresponds to a total decrease of Vdc mg. The volume of clean air entering the enclosure through the various "breathing" outlets of the structure during this time is Vdt, which is also the volume of contaminated air that leaves the building (the assumption has been made that ambient air entering the structure after the moment of measuring the initial concentration is pollutant-free). The contaminated air that leaves the enclosure contains cvdt mg of the pollutant. The flow is defined, as stated before, by

$$-Vdc = cvdt \qquad (18)$$

Integrating between the appropriate limits

$$\int_{c_0}^{c_f} \frac{dc}{c} = -\frac{v}{V}\int_0^t dt = -a\int_0^t dt \qquad (19)$$

where c_0 and c_f refer to an initial and final concentration at time $t = 0$ and $t = t_f$ = t-final, respectively; it is

$$\ln \frac{c}{c_0} = -at$$

and

$$c = c_0 e^{-at} \qquad (20)$$

Equation (20) provides the time history of the concentration of a pollutant given the value of the ventilation rate a. It is senn that the effective residence time, equal to the time for one air change, is the inverse of the ventilation rate, a, ($t = 1/a = V/v$). Details on how to experimentally measure the ventilation rate of a structure will be given in a subsequent section of this chapter. This approach is similar to the theory developed by Constance [138] who used the mixing factor κ. His equation, corresponding to Equation (20) in this text, is

$$c = c_0 e^{-\kappa at} \qquad (21)$$

where values of κ vary from 1/3 to 1/10

The major assumptions in this approach, and some of the difficulties to be expected in using the model, may be summarized as follows:

- Implicit in this theory is that the ventilation rate estimated is an overall rate: it includes infiltration, cleanup, circulation and re-entry of the air.
- It is assumed that the source of the pollutant introduces a certain concentration of the pollutant and stops operating (as in the instantaneous explosion of a gas munitions shell, the operation of a controlled aerosol spray, the passage of a transient puff of pollutant, or the turning on and off of a combustion source). The initial pollutant concentration is generated in one of two ways: (a) an inside source operates for a short time and then it stops, or (b) an ambient pollutant concentration appears as a cloud just outside the

> enclosure. A corollary of this is that the pollutant concentration inside the enclosure is assumed to disperse under the influence of infiltration of pollutant-free ambient air.
>
> The ventilation rate "a" is representative of the meteorological conditions prevailing during the introduction and monitoring of the tracer; at least three different sets of meteorological parameters should be investigated because the ventilation rate varies with respect to the wind, the temperature and the pressure gradients indoors and outdoors.

These assumptions and difficulties notwithstanding, the effective residency time approach is a powerful tool in modeling indoor pollution concentrations because it is compact, simple, and can be applied to many situations to meet or approximate the assumptions made. The next model to be described under the generic term of 'dosage' models is more detailed; it considers sources inside and outside the enclosed space and it provides for the existence of indoor pollution sinks.

The Dosage Model

The dosage modeling approach outlined in this section was proposed by Calder [103] in studying air penetration of buildings. This approach has been implemented in modeling penetration of dense vegetation by Milly and Thayer [428]. The framework of relating indoor air pollution levels to outdoor air pollution levels can be modeled in terms of differential equations. The component-approach followed in the dosage model differentiates it from the residence time model outlined earlier; the dosage model does not require all the assumptions made before but it is subject to its own constraints. It is more detailed, requires field data obtainable only over extended periods of indoor and outdoor monitoring, and requires extensive computer usage for its implementation.

The dosage model takes into account the several processes that cause different amounts of airborne contaminants (gaseous or particulate) to occur inside a building: (1) air taken into the building through windows and doorways, ventilation systems and cracks or leaks throughout the structure; (2) removal and decay processes including filtering and absorption by entry channels, oxidation, settling, absorption and adsorption by walls and furnishings, interior circulation filtering, etc.; (3) interior generation from sources such as fireplaces, stoves, smoking, cleaning and others; and (4) air exhaust through chimneys, windows, doors, vents or other exits. A small differential change in the amount of interior contaminant results in the following mass balance equation modeled in terms of the above processes:

$$dQ = (1 - k)\, r x_o dt - \kappa Q dt + q dt - r x_i dt \qquad (22)$$

where

Q = mass of interior contaminant (mg)

k = fraction of entering material filtered out by ventilating system or structure characteristic

r = air intake/exhaust rate (m^3/hr)

t = time (hr)

κ = rate of decay, settling and removal (hr^{-1})

q = interior generation rate (mg/hr)

x_o = outside ambient concentration (mg/m^3)

x_i = inside ambient concentration (mg/m^3).

If the above expression is divided by V, the interior volume, recalling that

$$x_i = \frac{Q}{V} \tag{23}$$

the result obtained is

$$d_{x_i} = (1 - k)\,\frac{F}{V}\;x_o dt - \left(\frac{F}{V} + \kappa\right) x_i dt + \frac{Q}{V}\,dt \tag{24}$$

Substituting $R = \frac{F}{V}$ = ventilation rate (hr^{-1})/ the equation becomes

$$d_{x_i} = \left[(1 - k)\,R_{x_o} - (R + \kappa)\,x_i + \frac{Q}{V}\right] dt \tag{25}$$

To use these equations prior knowledge is needed of the values of signature parameters such as the ventilation rate, filtering characteristics, decay rate, and pollutant concentrations indoors and outdoors. The approach is oriented towards a particular structure; the results refer to the investigated structure, to its type of a ventilating system, to the climatology or meteorology and to other specific conditions. The filtering constant k is a function of particulate size for aerosols and of the concentration for gaseous pollutants; it also depends on the condition and maintenance of the filter systems. The removal or decomposition rate (κ) depends on the type of pollutant being considered as well as particulate size and the nature of the indoor environment. Studies of these parameters have been undertaken in the past and there is some information available for certain types of structures; details are presented later in this chapter.

Returning to the mathematical formulation of the dosage model, if Equation (25) is integrated with respect to time over a monitoring period t_s (the parameters remaining constant over a short sampling period t_s). Equation (25) becomes

$$x_i \Big|_0^{t_s} = (1 - k) R \int_0^{t_s} x_o dt - (R + k) \int_0^{t_s} x_i dt + \frac{qt_s}{V} \qquad (26)$$

The time integrated concentration observed over sampling time t_s is defined as a dosage

$$D_o = \int_0^{t_s} x_o dt = \text{ambient outside dosage}$$

$$D_i = \int_0^{t_s} x_i dt = \text{ambient inside dosage}$$

Under the sampling assumption the dosage is defined as the product of the pollutant concentration and the time period of sampling for both the inside and outside environments. Now Equation (25) becomes

$$x_i(t_s) - x_i(t=0) = (1 - k) RD_o - (R + k) D_i + \frac{qt_s}{V} \qquad (27)$$

Equation (27) provides the relative pollutant concentration change over a certain time period as a *function* of the outdoor and indoor dosage, and the generation and decay rates of indoor pollution sources and sinks over the same time interval.

The concept of dosage, widely used in studies of chemical warfare by Milly and Thayer [430] and others, is of fundamental importance in designing monitoring strategies and in defining different building parameters. Several hypotheses may be examined relative to the Equation (27) in order to determine sampling procedures. For instance, it may be difficult or impossible to measure instantaneous inside concentrations of some pollutants, e.g., particulates. If sampling is done over a sufficiently long time period, the difference in initial and final concentrations may be assumed to be unimportant relative to other terms in the equation. If the generation of the pollutant from inside sources is also negligible the model reduces to the following form

$$\frac{D_i}{D_o} = \frac{(1 - k)\,R}{R + \kappa} = B \qquad (28)$$

where

B = penetration ratio between accumulated inside and outside dosages.

If the penetration ratio is found to be near unity for a particular pollutant the effect of intake screening (k) and decay and removal (κ) are negligible for that pollutant. Careful measurements of the inside and outside concentration histories of such pollutants can be used to establish the building ventilation rate. For instance, if the generation of pollutant from inside sources is negligible and $\kappa = k = 0$, then

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$$R = \frac{\chi_i(t_s) - \chi_i(0)}{D_o - D_i} \tag{29}$$

This equation gives the average ventilation rate over the sampling time period t_s.

The impact of a controlled airborne material, such as an internally released inert gas, for determining ventilation rate can also be seen in the above equations. In this case the outside concentrations can be considered negligible and the pollutant intake can be ignored. Since the gas is inert, it may be assumed that $\varepsilon = 0$. Thus, the only measurements required to determine the ventilation rate are the internal concentrations. The equation is

$$R = \frac{\chi_i(0) - \chi_i(t_s)}{D_i} \tag{30}$$

Equation (30) provides an easy way of determining the overall building ventilation rate by introducing in the structure known concentrations of an inert gas, such as SF_6.

The power of the dosage model lies in its realistic approach to sampling because it does not necessitate instantaneous concentration readings which are indeed difficult for certain pollutants. It should be noted that the stated assumptions for various strategies can be achieved by imposing them, e.g., ceasing the generation of the indoor pollutant, $q = 0$, closing the various breathing vents, $k = 0$, or introducing an inert agent, $\varepsilon = 0$, and by sampling for long periods so that the difference between the initial and final concentrations may be assumed unimportant relatively to the other terms.

The "Well-Mixed" Tank Theory

A comprehensive theoretical study of the behavior of odorous vapors in the chambers was developed by Amos Turk [634]. Although this work specifically refers to odorous vapors the analytical principles involved are general and can be applied to all air pollutants. Turk's work has been utilized in subsequent studies relating indoor-outdoor pollution levels. His theoretical development is known as the "well-mixed tank" theory.

The theory is applicable to the general case of a chamber which contains an odorous vapor. The following processes are considered:

- A constant additional amount of vapor is generated, or injected into, the chamber per unit time
- The chamber air is being replaced by air from outdoors by ventilation or infiltration
- Sinks (vapor reducing devices) treat the chamber air.

A basic premise of the theory is that instantaneous and complete mixing of outdoor air takes place within the chamber. This is obviously not a wholly realistic model of what occurs, but provides an adequate representation of reality for the purpose of this model, which is to estimate a single average concentration value for odors (or other pollutants) inside air enclosed space. The premise is, in fact, common to all existing indoor-outdoor pollution models, in that they do not predict nor use data describing indoor pollution concentration gradients.

The notation which Turk used in his studies is as follows:

V = volume of chamber

t = time

C = concentration of vapor in chamber at any time

C_0 = initial concentration in chamber

C_∞ = concentrations of vapor in chamber at equilibrium

C_i = concentration of vapor in ventilation or infiltration

C_r = concentration of vapor delivered by the air treatment device

E = efficiency of vapor reduction by the air treatment device

Q_i = volume rate of ventilation or infiltration

Q_r = volume rate of air delivery by the air treatment device

G = quantity rate of generation of vapor within (or injected into) chamber

N = number of air changes

m = mixing factor

X = quantity of vapor in chamber.

At any given moment

$$C = X/V \text{ or } X = VC \qquad (31)$$

The vapor quantity X changes with time, dt, in the following fashion

$$dX = VdC \qquad (32)$$

This change is caused by three factors:

1. Generation = Gdt
2. Infiltration or ventilation: $- (C-C_i)\ Q_i\ dt$
3. Vapor reducing device: $- (C-C_r)\ Q_r\ dt$. It is $E = (C-C_r)/C$ which leads to the device effect: $- CEQ_r\ dt$

The total change dX follows the sum of the three factors

$$dX = VdC = Gdt - (C-C_i)\ Q_i\ dt - CEQ_r\ dt \tag{33}$$

and

$$\frac{-VdC}{[C\ (Q_i+EQ_r) - (C_iQ_i+G)]} = dt \tag{34}$$

Integrating Equation (34) between C_0 and C we obtain

$$-\frac{V}{Q_i+EQ_r}\ \ln\left[\frac{C\ (Q_i+EQ_r) - (C_iQ_i+G)}{C_0\ (Q_i+EQ_r) - (C_iQ_i+G)}\right] = t \tag{35}$$

or in a more practical form

$$C = C_0 \exp\left[- (Q_i+EQ_r)\ t/V\right] + \left(\frac{C_iQ_i+G}{Q_i+EQ_r}\right)$$

$$(1 - \exp\left[- (Q_i+EQ_r)\ t/V\right]) \tag{36}$$

The case of equilibrium is denoted by $t \to \infty$, hence any e^{-t} term goes to zero and Equation (36) becomes

$$C_\infty = \frac{C_iQ_i+G}{Q_i+EQ_r} \tag{37}$$

In his theoretical study Turk analyzed nine special cases:

Case 1: Ventilation air is pure ($C_i = 0$), and

$$C = C_0 \exp [- (Q_i+EQ_r)\ t/V] + \frac{G}{(Q_i+EQ_r)} (1 - \exp [- (Q_i+EQ_r)\ t/V]) \qquad (38)$$

$$C_\infty = \frac{G}{(Q_i+EQ_r)} \qquad (39)$$

Case 2: No internal sources or injected vapor concentrations ($G = 0$), and

$$C = C_0 \exp [- (Q_i+EQ_r)\ t/V] + \frac{C_i Q_i}{(Q_i+EQ_r)} (1 - \exp [- (Q_i+EQ_r)\ t/V]) \qquad (40)$$

and

$$C_\infty = \frac{C_i Q_i}{(Q_i+EQ_r)} \qquad (41)$$

Case 3: The vapor reducing device is 100% efficient ($E = 1$ and $C_r = 0$), and

$$C = C_0 \exp [- (Q_i+Q_r)\ t/V] + \left(\frac{C_i Q_i+G}{Q_i+Q_r}\right) (1 - \exp [- (Q_i+Q_r)\ t/V]) \qquad (42)$$

and

$$C_\infty = \frac{C_i Q_i+G}{(Q_i+Q_r)} \qquad (43)$$

Case 4: The chamber is originally pure ($C_0 = 0$), and

$$C = \frac{C_i Q_i+G}{Q_i+EQ_r} (1 - \exp [- (Q_i+EQ_r)\ t/V]) \qquad (44)$$

and

$$C_\infty = \frac{C_i Q_i + G}{Q_i + EQ_r} \text{ = the general equilibrium equation} \qquad (37)$$

Case 5: The chamber (room) is tight ($Q_i = 0$), and

$$C = C_0 \exp\,(-\,EQ_r\ t/V) + \frac{G}{EQ_r}\,[1 - \exp\,(-\,EQ_r\ t/V)] \qquad (45)$$

Case 6: Combinations of Cases 1 and 2 ($C_i = G = 0$), and

$$C = C_0 \exp\,[-\,(Q_i + EQ_r)\ t/V] \qquad (46)$$

and

$$C_\infty = 0 \qquad (47)$$

Case 7: Combinations of Cases 1 and 3 ($C_i = 0$, $E = 1$, $C_r = 0$), and

$$C = C_0 \exp\,[-\,(Q_i + Q_r)\ t/V] + \frac{G}{(Q_i + Q_r)}\ \{1 - \exp\,[-\,(Q_i + Q_r)\ t/V]\} \qquad (48)$$

and

$$C_\infty = \frac{G}{Q_i + Q_r} \qquad (49)$$

Case 8: Combination of Cases 2 and 5 ($G = 0$, $Q_i = 0$), and

$$C = C_0 \exp\,(-\,EQ_r\ t/V) \qquad (50)$$

and

$$C_\infty = 0 \tag{51}$$

Case 9: Combination of Cases 1, 2 and 3 ($C_i = G = C_r = 0$, $E = 1$), and

$$C = C_0 \exp\left[-(Q_i+Q_r)\, t/V\right] \tag{52}$$

and

$$C_\infty = 0 \tag{53}$$

Continuing with his theoretical study Turk refers to the concept of air exchange defined as the number (N) of air changes per unit time

$$N/t = Q/V$$

or

$$N = Qt/V \tag{54}$$

Turk recognizes, in his discussion of the "well-mixed" tank theory, the mixing of outdoor air with air already in the chamber may take place over time intervals sufficiently long so that the premise of instantaneous mixing becomes invalid for modeling purposes. He notes that concentration fall-off rates will then be smaller than the ones which would result from the ideal instantaneous mixing. A mixing factor as which, according to Uriuf [89] ranges between 1/3 to 1/10, is applied to correct for this. Turks's work has been used in all subsequent studies relating indoor-outdoor air pollution levels.

The "Black-Box" Model

Hunt and others at NBS in an indoor air pollution status report [318] have developed a methodology called the "black box" model of a building with forced ventilation. Figure A-2 indicates the major components of the simulated structure. Equation (55) shows the relationship among the various factors entering into the "black box" model.

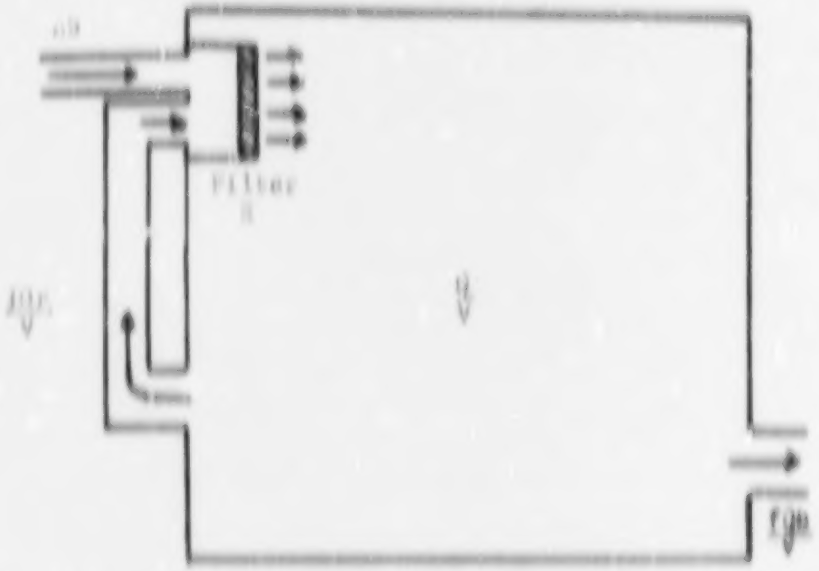

Figure A-2. Schematic representation of a ventilated enclosed space [318].

$$\frac{dQ}{dt} = ab(1-E) + G - QEr - \frac{Qb}{V} \qquad (55)$$

Rate of change of total pollutant with time	Rate entering in fresh air	Rate generated in enclosed space	Rate removed by filteration	Rate removed by exhaust

where

Q is the total amount of pollutant in the enclosed space
v is the volume of the enclosed sapce
a is the concentration of pollutant in outside air
b is the volume rate at which outside air is brought into the space
E is the efficiency of the filters
G is the rate at which pollutant is generated in the enclosed space
r is the volume rate at which air is recirculated.

Equation (55) is expressed as

$$\frac{dQ}{dt} = A - BQ \tag{56}$$

where

$$A = ab(1-E) + G$$

$$B = \frac{ER + b}{V}$$

Treating all parameters involved as constants, Hunt performs a series of straightforward mathematical steps and arrives at the following solution of Equation (56).

$$Q = \frac{A}{B}\left(1-e^{-Bt}\right) + Q_0 e^{-Bt} \tag{57}$$

$$Q_\infty = \frac{A}{B} \text{ for steady state at } t = \infty \tag{58}$$

Obvious similarities between the Turk and Hunt studies should be noted. The concept of response time is introduced by the Hunt study.

The response time of an enclosed space is the time required for the indoor concentration of a pollutant to rise from zero to a given fraction of its steady state level. The response time is given by:

$$t = \frac{1}{B} \ln \frac{Q_0 - Q_\infty}{Q - Q_\infty} \qquad (59)$$

In theory infinite time is required for reaching steady state, however in practice Q approaches Q_∞ in relatively short time. It is of interest to note that while the outdoor concentration determines the magnitude of the indoor steady state concentration, it does not determine the time period necessary to reach the steady state. Under the stated assumptions the response time is a characteristic of the building only, see Equation (59).

Further investigation of the steady state expression, and rearrangement of the individual parameters leads to the following straight line equation:

$$\frac{Q_\infty}{V} = Ma + N \qquad (60)$$

where the slope

$M = \frac{b(1-F)}{Er + b}$ is the filtering factor, and

the intercept $N = \frac{Q}{Er + b}$ is the source-sink factor

The "black box" model has been applied for cases in which the outside concentration changes vary according to the following equation:

$$a = a_1 + a_0 \sin wt \tag{61}$$

where

a_1 is the average concentration
a_0 is the amplitude, and
w is the angular rate of change of the sine function.

The solution of Equation (62) is

$$q = \frac{A'}{B}(1-e^{-Bt}) + Q_0 e^{-Bt} + \frac{A_0' w}{B^2 + w^2}\ e^{-Bt} + \frac{A_0'}{B^2 + w^2}(B\sin wt - w\cos wt) \tag{62}$$

where

$$A' = a_1 b(1-E) + G \text{ , and } A_0' = a_0 b(1-E)$$

are the only symbols not previously explained. The authors of this study point out that the model can be applied to buildings with air conditioning and without air conditioning, but they however recognize many difficulties in obtaining infiltration/exfiltration rates for non-air conditioned structures.

The Linear-Dynamic Model

The linear-dynamic model described in the remaining pages of this section is the most recent product of an investigation of the indoor-outdoor pollution problem by Dr. Fredrick H. Shair and his research team [561]. Shair investigated relationships between indoor air pollution energy conservation with the objective of providing a basis for reducing energy utilized for heating the various California Institute of Technology campus buildings while minimizing indoor pollution levels; this was thus a theoretical and experimental (practical) research undertaking.

The linear-dynamic model, like previous models examined, is a mass balance flow analysis of a well mixed airborne pollutant. Figure A-3, shown below, diagrams the model and its component flows:

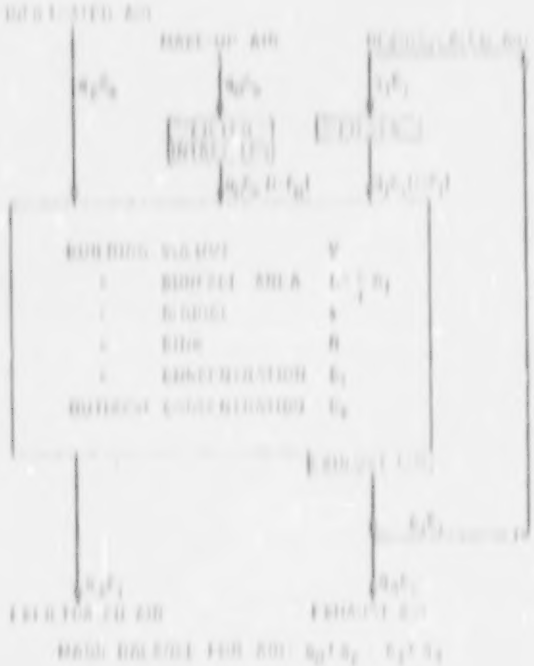

Figure A-3. Schematic diagram of ventilation model [561].
(Generally, makeup air and recirculated air both pass through the same filter and intake fan system.)

In this model the outdoor air, containing an ambient pollutant concentration enters a building of volume V by three distinct processes: (1) air penetrates into the enclosure from outside through doors, windows and cracks at a rate q_2; this is the infiltrated air; (2) it enters from the outside as make-up air via the "breathing outlets" and passes through a filter at a predetermined rate q_0; this is make-up or partially purified air; and (3) the air is circulated into the structure and reenters via the same or another filter at a rate q_1; this is the recirculated air. The air exits the building by (1) exfiltration through the same openings as for infiltration, and (2) exhaust ducts. The pollutant concentrations may be increased indoors due to internal sources operating at the rate S, and decreased due to internal sinks operating at rate R; the net rate of internal pollution generation is S - R. A factor F_0 describes the pollutant cleaning efficiency of the filter in the make-up air stream; it is

$$F_0 = \frac{C_{inlet} - C_{outlet}}{C_{inlet}} \tag{63}$$

where

C_{inlet} = the pollutant concentration in the air just prior to entering the filter

C_{outlet} = the pollutant concentration in the air just as it leaves the filter.

The pollutant cleaning efficiency of the filter for the recirculated air stream is characterized by a similarly defined factor F_1.

An infiltration rate for the building is defined by totally stopping the regulated structure breathing outlets, the remaining air flow into the building then occurs at the infiltration rate. In practice the infiltration rate can be measured in the building by quantifying the rate of air changes with the help of an inert gas.

The mass balance equation describing the above processes is:

$$V\frac{dC_i}{dt} = q_0C_0\ (1-F_0) + q_1C_i\ (1-F_1) + q_2C_0 - (q_0+q_1+q_2)\ C_i + S - R \qquad (64)$$

Previous knowledge of (1) the filter factors and their variations with time, (2) the infiltration rate of the structure, and (3) the generation and decay rates due to indoor sources and sinks, respectively, is required before any practical application of Shair's model is undertaken. The numerical values of these rates are obtained experimentally for each enclosure. It is convenient to make a series of parameter changes to nondimensionalize Equation (64); the new parameters are:

$$\theta_i = C_i/C_{ref},\ \tau = q_0t/V,\ \alpha = q_1/q_0,\ \beta = q_2/q_0,\ \gamma = \quad \kappa_jA_j/q_0,$$

$$\delta = 1 + \alpha F_1 + \beta + \gamma,\ \epsilon = 1 + \beta - F_0,\ \theta_0 = C_0/C_{ref},\ \text{and}\ \sigma = S/q_0C_{ref},$$

where κ_j is a decomposition rate on the jth surface with area A_j and refers to the indoor sinks, and C_{ref} is a reference concentration chosen for convenience. The new equation with nondimensional variables is:

$$\frac{d\theta_i}{d\tau} + \delta\theta_i = \epsilon\theta_0 + \sigma \qquad (65)$$

with solution

$$\theta_i = \varepsilon e^{-\Delta\tau} \int_0^{\tau} e^{\Delta\tau} \theta_o d\tau + e^{-\Delta\tau} \int_0^{\tau} e^{\Delta\tau} \sigma d\tau + \theta_{io} e^{-\Delta\tau} \qquad (66)$$

where $\theta_{io} = C_{io}/C_{ref}$ and C_{io} the indoor concentration at t=o. Equation (66) relates the indoor concentration to the outdoor pollutant concentration. Five time scales enter into the development of this model: the time t_1 relating to the changes in the outdoor concentration, and $\Delta\tau$ time to remove the enclosed air by one of the following four processes: (1) make-up air, (2) recirculated filtered air, (3) infiltrated air, and (4) time to remove the pollutant by a first-order decomposition (decay) mechanism. The value t_1 is either of the same order of magnitude (or smaller) or much larger than the inverse of the sum of the inverses of the four $\Delta\tau$ characteristic times. If t_1 is of the same or smaller magnitude than the sum, Equation (66) should be used in its totality for ventilation calculations. If t_1 is large with respect to the sum then the last term in the equation may be neglected. A series of useful approximations can be formulated and easy analytical solutions can be obtained. The outdoor pollutant concentrations are made to vary in an approximately sinusoidal manner in order to investigate the phase differences in the indoor-outdoor maximum concentrations. C_o is approximated by the expression $C_o = C_{io} +$ at over the time t_1 since:

> "Many cases of practical interest involve an input function which does not warrant the use of a sophisticated interpolating procedure in order to predict

> the pollutant concentration within a time interval defined by two successive data points." [561]

This model is the result of a series of theoretical and experimental steps. It is similar in its basic concept to the other models, but is more advanced and better validated than other analytical works.

An underlying assumption of this model is the uniformity of the pollutant concentrations; all gradients are neglected in this study. Emphasis is placed on the various ventilation rates of the structure. A previous knowledge of engineering parameters is required to implement this analysis. A validation study by Shair that followed the formulations of this model showed a favorable comparison of the theoretical and experimental results [561].

A.3 THE STATE-OF-THE-ART OF DEFINITION OF MODEL INPUT PARAMETERS

The principal existing indoor-outdoor air pollution models were discussed, in the previous section, on a model-by-model basis. The present section will review the state-of-the-art of definitions of the principal parameters common to most models, these being:

- Pollutant strengths and decay rates
- Indoor environment characteristics
- Structural characteristics
- Human activities
- Monitoring constraints.

The discussion which follows is not entirely derived directly from the scientific literature; it includes some concepts for parameter definitions which are now under development by the authors of the present report.

A.3.1 Pollutant Source Strengths and Decay Rates

The fate or time-history of a pollutant, once it appears indoors, is a complex function of a number of factors denoted by two generic terms: sources and sinks. Section 3.1 of this report described some investigations of the emission rates of source-strengths for pollutants generated indoors. The following conclusions emerge when the literature on indoor pollution source-strengths is viewed from the numerical modeling point of view:

- Experimental technology, including instrumentation accuracy and precision, and monitoring design vary widely. Owing to this variation, model calculations should be compared with experimental data on a trend-basis rather than on the absolute magnitude of the investigated parameter.
- Indoor generation rate estimates are subject to ±500 percent or more variation [141]. This large range of indoor pollution source-strength requires that numerical investigations be undertaken for average, per unit time, source strengths as well as for maximum and minimum indoor generation rates.
- The literature research has not produced evidence of research in which combined experimental and analytical studies were conducted to estimate indoor source strengths. The use of a detailed tracer experiment and the "backwards-integration" analytical approach may provide realistic estimates of the rate of emission of an indoor source. Details of this approach will be discussed in Section A.4.

Section 4.0 described previous research into pollutant behavior inside buildings, including the chemical decay and transformation of some pollutants. The chemical properties of pollutants are important; the numerical analyst must investigate all the processes and the relative importance of the various indoor sinks. It is appropriate to recall the characteristic times associated with mechanisms that may be considered indoor pollution sinks [561]: (1) a characteristic time to exchange the air with make-up air; (2) a characteristic time to remove the pollutant via the recirculation filter; (3) a characteristic time to exchange the building air with infiltrated air; and (4) a characteristic time to remove the pollutant via a first-order decomposition mechanism. The following general conclusion has been reached with respect to the relative order of the pollutant removing processes: From the model development point of view the chemical decomposition of the indoor pollutants is slow when it is compared to other processes included in the mass balance equation which simulates the indoor-outdoor air pollution levels [Shair (1976) private communication]. A direct result of this conclusion is that in many cases the model does not include a sink factor which refers strictly to the chemical pollutant behavior. Two notes of caution are necessary with respect to the above statement: (1) this conclusion does not apply to highly reactive pollutants, such as ozone or other oxidants, and (2) with respect to conservative pollutants, it is a general conclusion in need of more specific investigations and further validation.

A.3.2 Indoor Environmental Parameters

The indoor environmental parameters, temperature and relative humidity, are indirect parameters; by this it is meant that they do not explicitly enter into any of the reviewed indoor-outdoor air pollution models but they do affect pollutant decay rates, human activity, and building occupancy habits, and the operational modes of various indoor pollution sources. These two parameters must be investigated in order to search for correlations between them and the various explicitly stated input variables of indoor-outdoor air pollution models. Work of this nature has been reported in the literature, although not extensively. References to it are included in Section 4.0 of this document.

A.3.3 Structure Identification Parameters

Another set of indirect parameters is that of the structure identification parameters. Models require that air exchange rates be parameterized as a function of structure identification parameters. Building material descriptions such as density, heat capacity, thickness of the floors, walls, windows, ceiling; building descriptions such as area of the zones, height of the ceiling, height of plenum, lighting, heat systems, equipment operating schedules, type of mechanical system, and other control parameters constitute a partial list of the structure identification parameters. On the following pages a building information report format appears which is being used in conjunction with field monitoring work in an EPA-sponsored indoor air pollution research project now being performed by GEOMET. It is intended that the information gained from this report will be utilized in conjunction with a set of measured indoor and outdoor air pollution concentration levels, meteorological parameters and building ventilation rates in the formulation of an improved general indoor-outdoor air pollution model. This report format, which was developed by Hittman Associates, Inc., is included here because it defines structural parameters which are relevant for modeling purposes and because it furnishes information for future formulation of an algorithm relating building parameters and ventilation rates as an input in the indoor-outdoor pollution model.

STRUCTURAL AND ENERGY DATA

for

Indoor-Outdoor Air Pollution Study

Site__________________________________

Address________________________________

Type of Structure:

One Story ______

Split Level ______

Bi-Level ______

Story and a Half ______

Two Story ______

Three Story ______

Attached ______

Detached ______

Height of Building (feet)_____ Height of One Story _____

Total floor area in structure (square feet) _____

Glass area as percentage of floor area (excluding glass doors)

Are structures oriented so that glass area is distributed in particular direction? _____yes _____no

If yes, what is the approximate distribution of glass area by sides of structure?

North _____% South _____% East_____% West _____%

If glass area is distributed in no particular direction, assume structure faces North.

Does structure have basement? _____Full _____Half _____No

Heated? _____Full _____Half _____No

If no basement, what is beneath floor:

_____Concrete slab _____Crawl space

If crawl space, is there insulation under floor? _____Yes _____No

If Yes, type and amount? __________________________

If full or partial unheated basement, is there insulation under floor?

_____Yes _____ No

If Yes, type and amount? __________________________

Is there an attached, enclosed garage? ______Yes ______No

Heating System

______Oil

______Gas

______Electric

______Other Fuel

______District Steam

______Heat Pump

______Solar Assisted

Distribution System

______Air

______Steam

______Water

______1 pipe

______2 pipe

______3 pipe

______4 pipe

Cooling System

______Electric

______District Chilled

______Water

______Absorption

______Oil

______Gas

______District Steam

If electric heat, central or radiant?

If electric cooling, central, or individual units?

Central Individual

Hot water heating fuel is: ______oil ______gas ______electric

______district steam

Describe the external color of building walls.

______Light ______Dark

Number of Exterior Doors (excluding glass doors per structure).

1, 2, 3, 4, ______, 1 per unit

Door Material ______________________________

No. of sliding glass doors per structure, 1 per unit ________

orientation of glass doors - N S E W

area per door ______sq. ft.

Do the units have balconies? _____Yes _____No

If yes, give dimensions _____ft. wide x _____ft. long

Type of Roof - Peak or Gable (height = _____'), flat, built-up (high rise)

Exterior Wall Construction - Material and dimension or overall "R" value

	Ext. Wall	Ext. Wall		
Layer	Type 1	Type 2	Roof to Ceiling	Party Wall

Windows: Frame material - wood aluminum

Glazing - single, double, triple

Storm windows? ______Yes ______No

Exterior dimensions of Building - _____ft x _____ft

Sketch of Floor Plan:

A.3.4 Human Activity Information for Modeling

Human activities impact upon indoor air quality through the ways in which people use building ventilation systems, entrances, and windows, and through the use of pollutant-generating materials and equipment indoors. The frequency and duration of occupancy of various indoor spaces is an important factor necessary to adequately determine indoor pollutant exposure episodes. This type of information is usually collected by researchers through subject interrogation. The literature of this type of research has been reported in Section 6.0, with examples of the occupancy and activity profiles used to quantify the behavior of people moving and engaging in various activities within structures. The reader is referred to Section 6.0 of this report for a discussion.

The literature review has revealed that various occupancy profile sources can be found, but few of these sources include profiles of distribution of occupancy within a building. The variation among occupancy profiles from different sources indicates the wide range of occupancy profiles for individual buildings. Any sampling of buildings to determine an average occupancy profile is likely to show some variation from any other sampling of the same population of buildings. But all of the profiles found for any one building type do have the same general form; and although some variation is present, they are very much alike.

Another important aspect of human activity is represented by the information to be gained through daily diary logs of human activity in a home. An example of such a log follows:

Daily Activity Log

SITE:

DATE:

1) Did you cook breakfast? From when to when? How many burners were used?

2) Did you cook lunch? From when to when? How many burners were used?

3) Did you cook dinner? From when to when? How many burners were used?

4) Did you have guests? From when to when? If yes, how many? Between what hours?

5) Did you do special cooking (baking, for example) which took more cooking time than noted in (1), (2), and (3)?
If yes, when?

6) Did you do any cleaning?
If yes, what kind of cleaning material did you use?

7) Did you or your guests smoke? What type of smoking (cigarette, cigar, etc.) and for how long?

8) Did you use an air freshener?
If yes, what kind (brand) at what times?

9) Did you use any aerosols?
If yes, what kind (brand) at what times?

10) Did you open the windows?
If yes, between what hours?

11) Did you vacuum?
If yes, from when to when?

12) Did you turn on the range hood fan while cooking?

13) Did you use a fireplace? When?

14) Was there a period of time that nobody was home, what hours?

A.3.5 Monitoring Constraints on Model Characteristics

The air pollution monitoring networks used to obtain data for development and validation of models are constrained by the state-of-the-art. Models use the best available sets of data, but they are not the ideal sets. Data used in modeling must be considered with respect to its reliability; it is necessary to know the types of instruments used, their detection limits, response times and sensitivity. The location of sampler probes is critical; are the probe sites representative? The design of the monitoring system is important, including procedures for calibration and quality assurance. The importance of these factors becomes apparent when comparative studies are undertaken.

The nature of the pollutants impose constraints on the modeling approach. For example, a realistic averaging time for particulates may result in eight-hour samples because no instrumentation exists to give reliable measurements of particulates gathered in shorter times at the low concentrations prevailing in some non-workplace environments. This example would impose an eight-hour time period on the modeling study of indoor particulates, while one-hour or smaller time periods would be considered for gaseous pollutants.

A.4 A PROVISIONAL GEOMET DESIGN FOR AN INDOOR AIR POLLUTION MODEL

GEOMET is now engaged, as a part of its current EPA-sponsored program of indoor air pollution research, in planning for the future development of an improved indoor air pollution simulation model which will build upon the existing body of research (just described) and which will rely for additional field data and preliminary validation upon a program of field monitoring of indoor air pollution and related parameters which is now underway.

A provisional design for major elements of the planned GEOMET model has been developed. The model is built upon the concepts of the linear-dynamic model of Shair [561]. But the Shair model and all other previous modeling studies described in this report have assumed that there are no air pollution gradients within a structure. In the GEOMET program it is planned to introduce the concept of interior zones within the building. Each zone may have its own pollution concentration level. The concept assumes uniform mixing within each designated zone but effectively provides a means of describing stepwise pollutant concentration gradients within a structure. To make the assumption of uniform pollutant mixing within each zone a realistic assumption and to simulate true gradients it will be necessary to have a large number of zones in each structure, i.e., zones must be small.

Two important parameters of the planned GEOMET modeling effort are the "breathing" rates, and the efficiency coefficient of the indoor pollution control equipment. "Breathing" rate is a generic term used for a total building air change rate; it represents the sum of ventilation rate and the infiltration/exfiltration rates. Measurement of the ventilation rate will be critical for model accuracy.

A.5 USE OF TRACER GASES IN MEASUREMENT OF VENTILATION RATES AND OTHER ASPECTS OF INDOOR AIR POLLUTION MODELS

Development of a zoned indoor pollution model will require the calculation of ventilation rates through field measurements with a tracer gas. To measure the total air change rate of a building a known amount of an inert tracer gas, for example, sulfur hexafluoride (SF_6), is emitted into the enclosed space. The concentration of this tracer is monitored for a certain time period, and the ventilation rate is obtained from the slope of a semilog plot of the natural logarithm of the pollutant concentration vs. time. The equation

$$c = c_0 e^{-a t}$$

indicates that the slope is the ventilation rate a. A point of importance, for it helps validate the a value, is integration of the concentration-time curve which should produce the originally introduced tracer amount; such an approach has been successfully undertaken under carefully controlled conditions [149].

The air exchange rates of a dwelling can be determined by an experimental methodology which requires simultaneous continuous and grab sampling monitoring, there are two approaches:

- The three-outlet approach, which provides the skeleton of the breathing rates of a dwelling
- The detailed-comprehensive approach, which monitors every structural division of a residence (rooms, halls, closets) and furnishes data for the zone-concept.

The three-outlet approach monitors the tracer in three indoor locations on a continuous basis for a 12-hour period. The comprehensive approach is a grab sampling technique that requires samples on a half-hourly basis for each room and hallway for a twelve-hour period. The three outlet continuous tracer monitoring approach follows established methodologies which will not be repeated here. The comprehensive approach is outlined in the following paragraphs.

The tracer concentrations are monitored one time per hour in every room and hallway of the investigated dwelling. Assuming that the tracer is SF_6, the grab sampling can be done with plastic syringes of 10-30 cc's; the syringes must be carefully marked to indicate the location and the time of the sampling. The plastic syringes can be easily closed and transported from the experimental site to the laboratory for analysis. In work conducted by Dr. Fredrick Shair at California Institute of Technology, it has been shown that the SF_6 concentration inside the syringe will not change for two weeks [private communication from Dr. Fredrick Shair, 1976] which is adequate time for the required transportation from the field to the laboratory. During the twelve-hour period of tracer experimentation of the occupants' behavior must be kept, such a diary will provide data for a correlation between occupancy habits and infiltration/exfiltration and ventilation rates. Structural and HVAC system data will also be obtained.

This approach, using tracer studies to determine interior air flow characteristics combined with other field data, will provide: (1) the details of the structure's air channels; necessary information for the formulation of the zone concept; (2) the influence on each structural division (rooms, hallway, closet) of brief openings of doors or windows; (3) the rate of mixing as a function of geographical location within the structure; and (4) the necessary data for an integration to estimate, analytically, indoor-generated pollutant source strengths from an experimental reading at a certain distance from the source.

Hunt and Burch [317] have reported on their study of "Air Infiltration Measurements in a Four-Bedroom Townhouse Using Sulfur Hexafluoride as a Tracer Gas." After providing the structural characteristics of the unoccupied townhouse they describe its air distribution system, which consisted of a duct system leading to the rooms and a common return located in a hallway. A circulating fan forced air through the furnace and into distribution ducts leading to the various rooms. SF_6 was introduced into the circulating fan and distributed through the house. A gas chromatograph was used to measure the tracer concentrations; this instrument was calibrated three or four times during the course of each air exchange measurement against a known SF_6/air mixture concentration. Air samples were taken at specific times and were analyzed for SF_6. Three different sampling methods were used:

- Composite samples were collected manually with a hand pump and a balloon, going from room to room in a predetermined order; upstairs and downstairs were considered two different entities.
- Samples were collected through a sampling network consisting of 16 polyethylene tubes of identical length having a 6mmID. At least one tube extended to each of the rooms and hallways and converged at a common point, passing into a 12 liter/minute diaphragm pump.
- Samples were taken from the return air at the entrance to the main ventilating fan in the central air system.

The authors state that the first two methods are "usually not practical" for occupied houses; a special check was made to avoid tracer entry error by monitoring at strategically chosen locations, near the reentry duct. They also took simultaneous experimental readings by using both helium and SF_6 air exchange to check the possible significance of molecular diffusion; helium is expected to have six times the molecular diffusion of SF_6. Though the agreement of simultaneous measurements was not perfect, the difference was not large, see Figure A-4. The flow through buildings due to the stack effect was calculated by the following empirical relationship found in the ASHRAE Handbook of Fundamentals:

$$Q = 9.4\ A\ \sqrt{h\ (t_o - t_i)} \tag{67}$$

where

Q is the air rate in cubic feet per minute

A is the free area of inlets or outlets (assumed equal) in square feet

h is the height from inlets to outlets in feet

t_i is the average temperature of indoor air in height h

t_o is the temperature of outdoor air (F).

If the inlets and outlets are at the same level, h equals zero, and there is then, of course, no vertical air flow and no stack effect. From Equation (67) one estimates the infiltration rate in air changes per hour as follows:

$$N = 60\ Z/V \tag{68}$$

Where V is the volume of the investigated structure. Figure A-4 illustrates some of the results of this study.

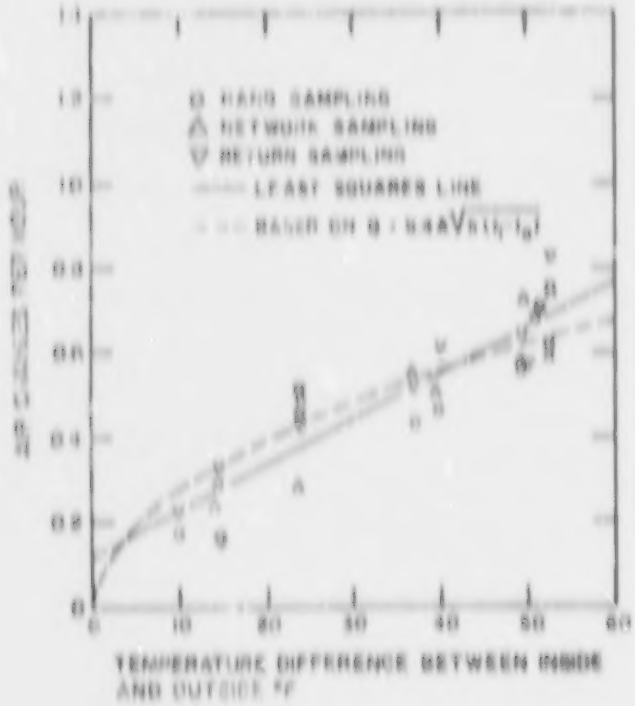

Figure A-4. Infiltration rate as a function of temperature difference between inside and outside [317]

Filter efficiency in air cleaning systems affects air flow rate through the system as well as impacting upon the removal of pollutants. A preliminary survey of available air filters for the cleaning of ventilation air or recirculated air for the conditioning of residential buildings, indicates a wide variety of efficiencies and particle holding characteristics are obtainable. Various operating characteristics of air filters are required in order to establish a means of rating each filter. These characteristics include filter efficiency, air flow resistance and particle or dust holding capacity. This subject has been discussed in Section 7.0.

A.6 CONCLUSIONS

At the minimum, an indoor-outdoor air pollution model must provide a framework within which it is possible to estimate pollutant concentrations indoors in terms of specifications of corresponding pollutant characteristics immediately outside an enclosed space, and the structural and energy data of the building itself. The reviewed indoor-outdoor air pollution models achieve this minimum requirement for a given structure; further research is needed to generalize the application of the models.

The following conclusions can be drawn from the study of existing indoor-outdoor air pollution modeling research.

- The fundamental principle involved is straightforward, (a mass balance equation) and theoretically sound. It has been used by all researchers who have developed indoor-outdoor ventilation and air pollution models.

- All practical applications of the existing models require a prior knowledge of a rather large number of coefficients and constants included in the model expressions. Extensive field work is necessary to obtain these necessary factors.

- There are many knowledge gaps: Internal pollution generation and indoor source strengths must be studied more extensively; indoor sinks (decay rates) need more attention; indoor pollution levels are affected by the energy conversation measurements, by the inhabitants' activity factors, by the home structural characteristics and others; these relations are inadequately known at present.

The most difficult research problem identified in this appraisal of the literature of indoor air pollution modeling is in the effort required to determine the constants of the basic functional relationship simulating the indoor-outdoor air pollution levels. The reviewed models have avoided this difficulty by considering only one investigated structure and by experimentally determining these coefficients for a unique structure. One objective of new modeling effort now being sponsored by EPA is to formulate a model that may be applied to any given building under varying conditions. In GEOMET's current work for EPA toward this goal a series of parameterization procedures will be undertaken to use, in acceptable model input form, data from a current field study now underway and data from past field studies found in literature. The following parameters must be studied and connected by functional or associative numerical relationship.

- Outdoor pollution levels
- Indoor generation of pollutants
- Building permeability (ventilation, infiltration rates)
- Meteorological conditions (indoor/outdoor)
- Ventilation system capacity
- Building identification parameters, including zones
- Energy conservation factors
- Indoor pollutant behavior
- Human activity factors
- Indoor air pollution control instrumentation

A model capable of interrelating these factors, using data readily obtainable by state-of-the-art monitoring and field survey technology, and fitted with coefficients of general applicability, would represent a very substantial advance upon existing modeling capabilities. This is the objective, perhaps only in part achievable at present, of work now in progress.

Appendix B

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